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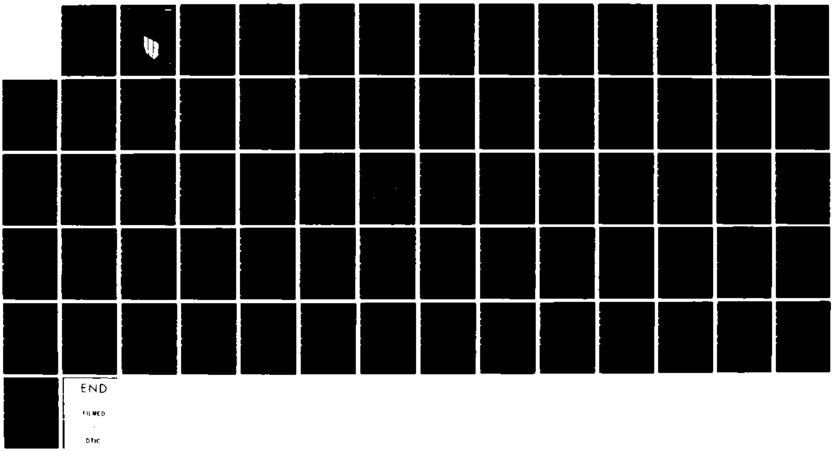

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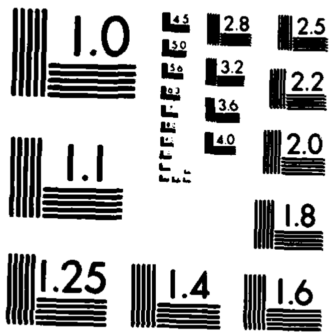


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US Army Corps
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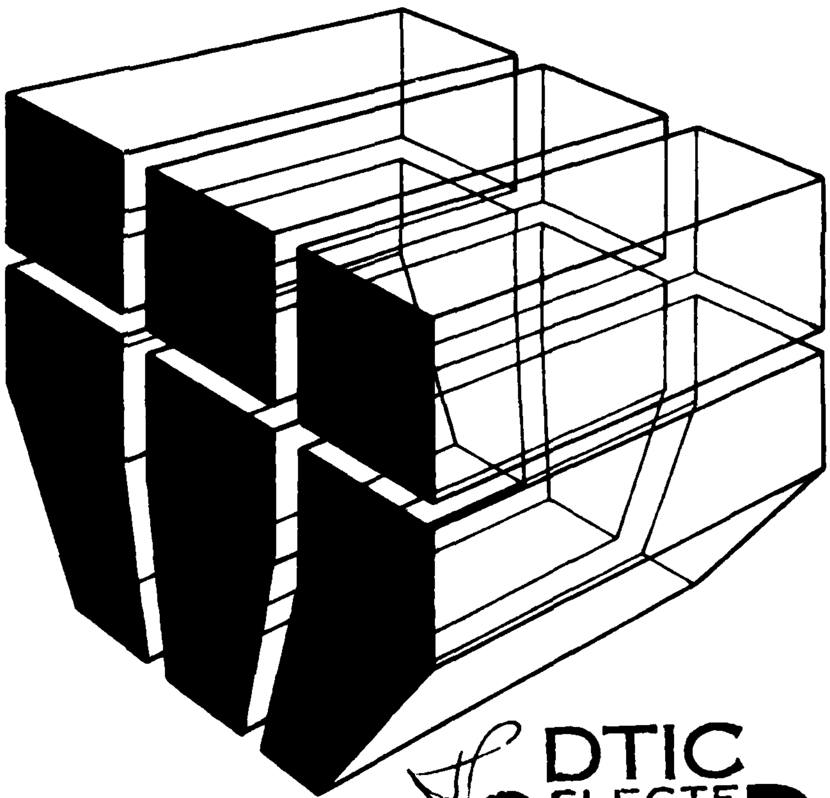
TECHNICAL REPORT E-196
July 1984
Modernization of Energy Systems in DARCOM Industrial Plants

# INVESTIGATION OF POWER FACTOR CONTROLLER APPLICATIONS





by
Mary B. Chionis
Ben J. Sliwinski





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This study was conducted to evaluate the power factor controller (PFC) as a potential energy conservation device for Army applications and to develop guidelines for its use. An examination of studies conducted on the PFC showed that it can be an effective energy conservation device when properly applied, cutting motor energy consumption by at least 10 percent on low-efficiency motors. However, the use of high efficiency motors is almost always more energy conservative, and PFCs do not improve the performance of motors whose efficiency is already high over the load range.

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There appear to be no serious drawbacks to the installation and use of PFCs. Problems caused by the generation of harmonics and the occurrence of motor instability have been reported but can be resolved by working with the PFC manufacturer.

It is recommended that power factor controllers be used as a retrofit energy conservation measure when their cost is low compared to the cost of replacing existing low efficiency motors with high efficiency motors. High efficiency motors should be selected when new motor-driven equipment is purchased.

## FOREWORD

This work was initiated as part of a reimbursable effort sponsored by the U.S. Army Materiel Development and Readiness Command (DARCOM) under IAO-82-077, and continued as an RDT&E project for the Assistant Chief of Engineers under Project 4A162781AT45, "Energy and Energy Conservation"; Technical Area B, "Installation Energy Conservation Strategy"; Work Unit 010, "Modernization of Energy Systems in DARCOM Industrial Plants." The work was performed by the Energy Systems Division (ES), U.S. Army Construction Engineering Research Laboratory (CERL). Mr. B. Wasserman (DAEN-ZCF-U) and Mr. G. Aveta (DRCIS-C) were the Technical Monitors.

The authors wish to express their appreciation for the efforts of Mr. Richard Campbell and Mr. Darren Gray in compiling and reviewing the documents used in this report.

Mr. R. G. Donaghy is Chief of CERL-ES. COL Paul J. Theuer is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

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# INVESTIGATION OF POWER FACTOR CONTROLLER APPLICATIONS

## 1 INTRODUCTION

### Background

The U.S. Army has long been concerned about its electrical energy consumption. In addition, it has been mandated that by 1985 the Army reduce overall energy consumption in facilities operations 20 percent over the 1975 baseline. Studies by A. D. Little and others indicate that electric motors consume two-thirds of all electrical energy generated in the United States.[1] One possible energy conservation device for electric induction motors is the power factor controller (PFC), which is supposed to save power by reducing the voltage and current to approach the amount necessary to meet the demand of lightly loaded motors.

Since the invention of the original power factor controller in 1975, several companies have produced and are marketing single-phase PFCs, and the concept has been extended to three-phase devices.[2] Questions have arisen regarding applications of PFCs. To use such devices most effectively, it is necessary to determine the degree of energy savings they can achieve, the amount of power factor improvement which occurs, and what drawbacks, if any, there are in application of the device.

The U.S. Army Materiel Development and Readiness Command (DARCOM) Energy Office, as part of its efforts to reduce energy consumption while maintaining mission readiness, asked the U.S. Army Construction Engineering Research Laboratory (CERL) to evaluate applications for the PFC.

### Objective

The objective of this study was (1) to examine the use of the power factor controller as an energy conservation device by investigating the characteristics of the device and determining its advantages and disadvantages, and (2) to develop guidelines for its use.

### Approach

The following approach was taken to accomplish the study objective.

1. Gather background information on the theoretical operation and scientific principles of the PFC.

2. Study results from actual PFC testing.

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[1] Army Energy Plan (U.S. Army Energy Office, Department of the Army, 1982).
[2] Power Factor Controller, Brief No. MFS-23280 (April 1979), p 3.

3. Review case studies of PFC usage.

4. Evaluate PFC economic analysis and power savings estimation techniques.

5. Develop Army guidelines.

## Mode of Technology Transfer

It is recommended that the conclusions and recommendations of this report be disseminated in an Engineering Technical Note.

# 2 THEORY OF PFC OPERATION

The power factor controller was designed by Frank Nola at NASA's Marshall Space Flight Center to reduce energy consumption by pump and fan motors in solar energy systems. After initial testing at Auburn University,[3] the device was patented in October 1977. The Auburn study indicated that the PFC afforded energy savings and minimized motor wear.

The initial design was for single-phase operation, but three-phase designs are now available commercially. These are essentially an adaptation of the original design using three silicon control rectifier (SCR) pairs which are controlled by electronic circuitry and synchronized for three-phase operation.

The basic design uses electronic circuitry to monitor the time difference between the voltage zero crossing and the current zero crossing, a function of power factor. Power factor is a function of motor load, which allows the PFC to sense load and control power flow to the induction motor. The time interval between voltage and current zero crossings is denoted "zero crossing time interval" (ZCTI). Under sinusoidal operating conditions this interval is directly proportional to the motor power factor angle. Figure 1 is a block diagram outlining the major functions of the basic device.

For the three phase PFC, each phase is provided with independent voltage-sensing circuitry and SCR pair for power control. A central unit provides phase synchronization for stable operation. Figure 2 shows the timing diagram. A ramp signal, synchronized with the line voltage, is generated by gating circuitry. Monitoring the line current and voltage allows information concerning ZCTI to be known. The measured ZCTI is compared to a reference ZCTI to generate an error signal. From Figure 2, it is clear that when the error signal drops below the reference ramp wave, a control signal pulse is generated which turns the SCR on. When the pulse goes low, the SCR is once again in a blocking (or nonconducting) mode. The SCR switching produces motor voltage and current signals similar to those in Figure 2. The angle represents the ZCTI and can be minimized by adjusting the PFC control circuitry. However, the angle $\Theta$ is the only variable optimized, and it is quite possible that unstable operation or motor stalling will occur when transient loads are placed on the motor. Decreasing the power factor angle minimizes reactive power flow, as seen in Equation 1.

$$Q = VI\sin\Theta \qquad \text{[Eq 1]}$$

where Q = reactive power (VARS)
V = voltage amplitude
I = current amplitude

[3] Dallas W. Russell and James L. Lowry, Evaluation of Induction Motor Performance Using an Electronic Power Factor Controller, NASA NCA-00128 (Auburn University, 1977).

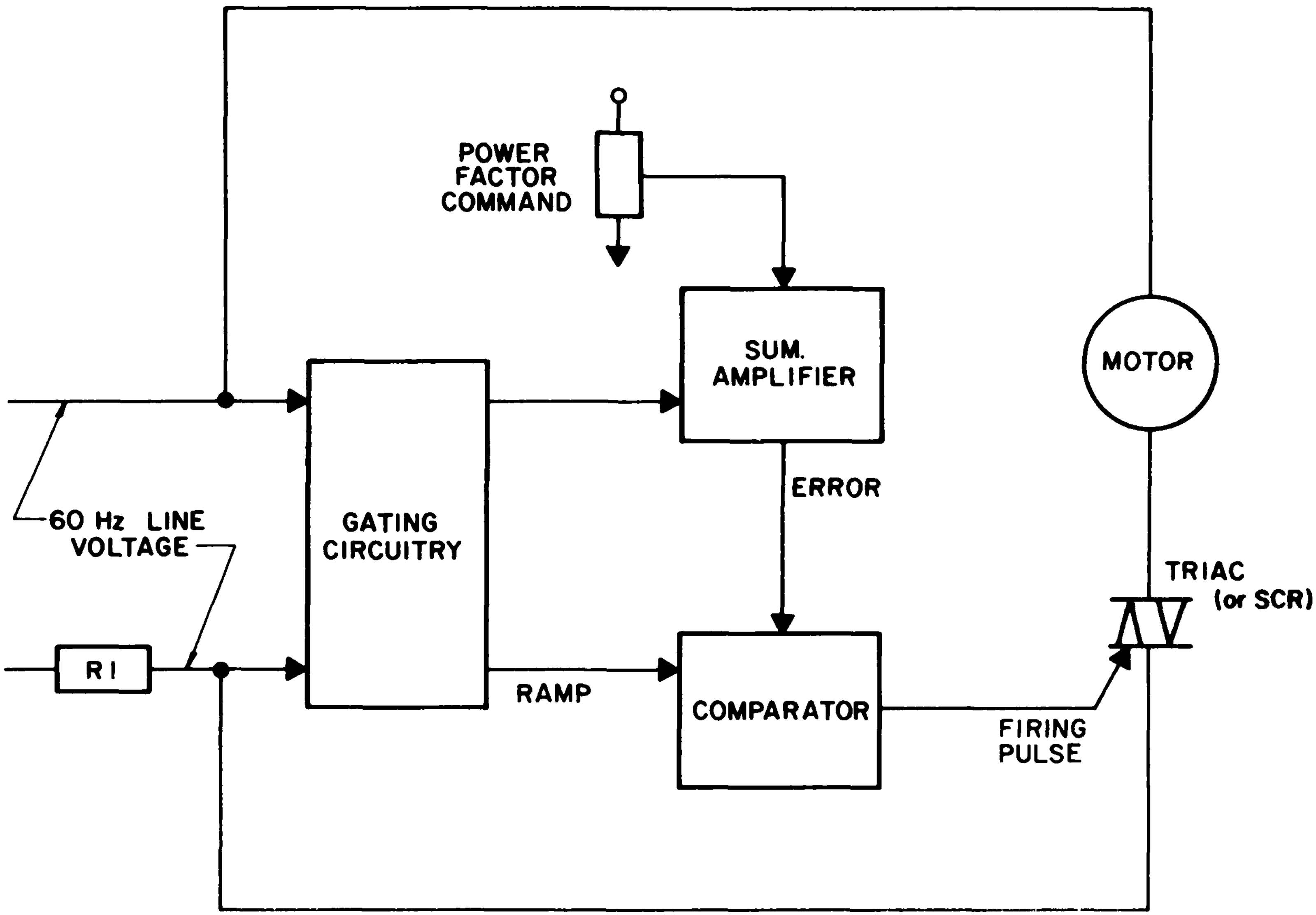


Figure 1. PFC block diagram.

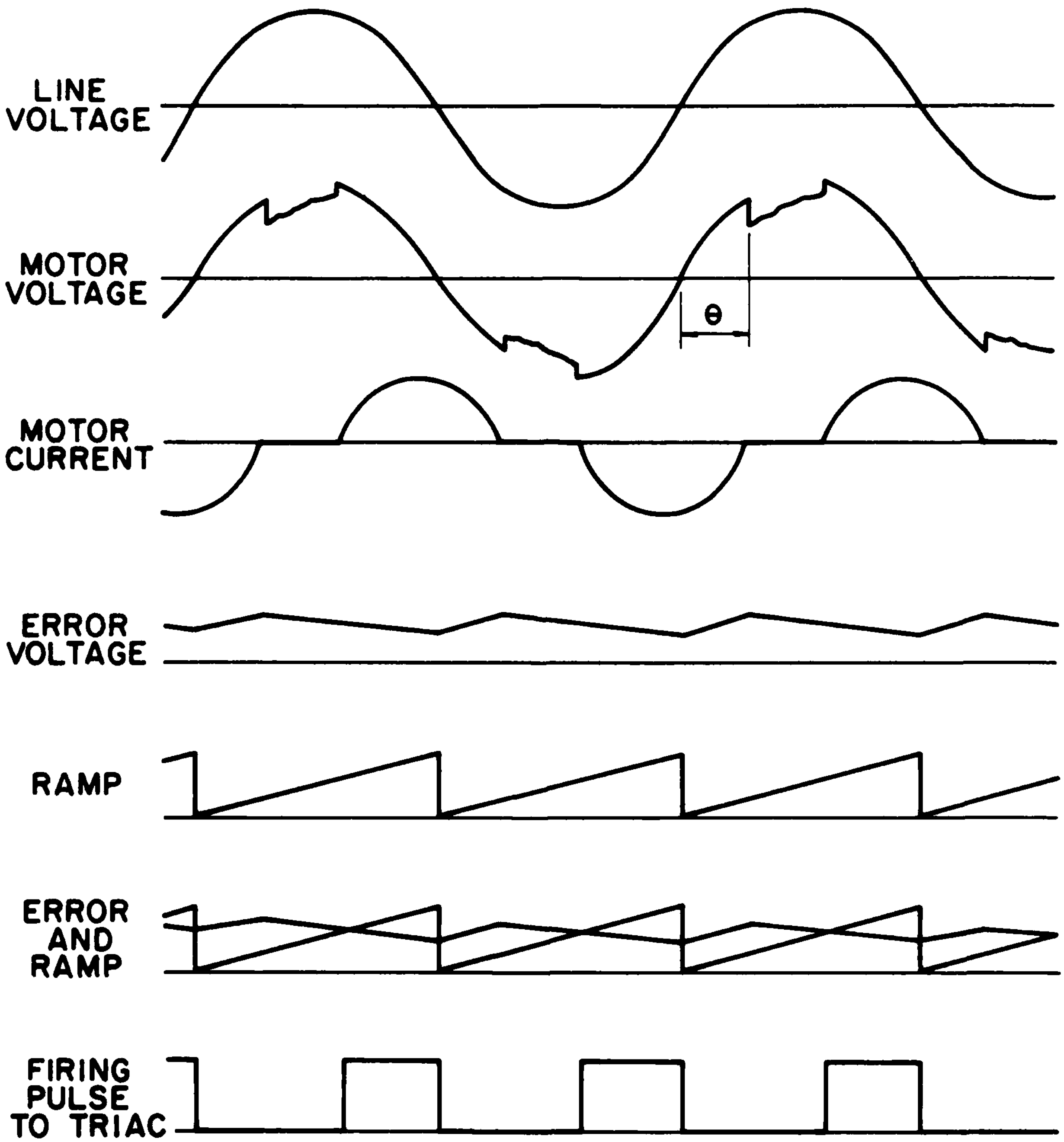


Figure 2. PFC timing diagram.

Reactive power in motors does no useful work and appears as $I^2R$ losses where R is the resistance. Figure 3 shows the net effect of voltage control offered by the PFC. When the current crosses zero it is turned off until the voltage reaches a maxima or minima, then it is turned on again. For a smaller current magnitude (current 2), the current is off for a longer time (ZCTI). Note how the voltage and current waveforms are brought into step.

Figure 4 represents the typical power savings for a single-phase motor.

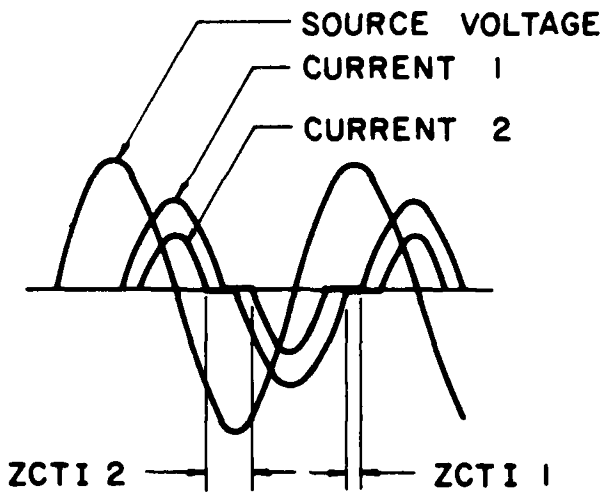


Figure 3. Zero crossing time intervals.

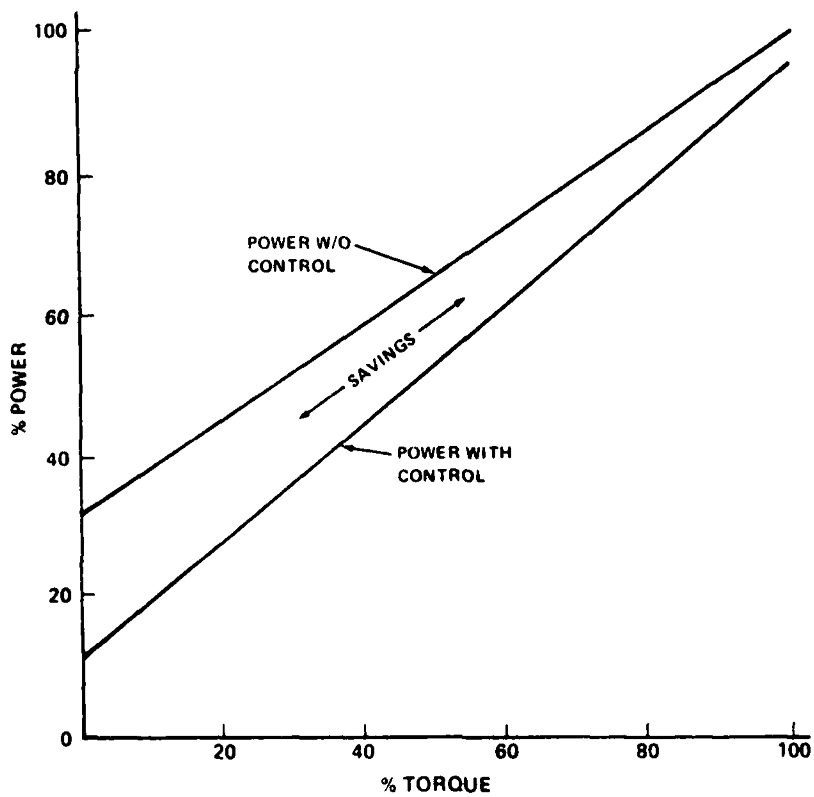


Figure 4. Typical power savings for single-phase motor. (From Power Factor Controller).

# 3 SUMMARY OF COMPLETED STUDIES

## Auburn Report[4]

The Auburn study of the PFC evaluated the process of reducing energy losses in induction motors by electronically controlling the phase shift between applied line voltage and armature current. Russell and Lowry divided their analysis into four parts: (1) the effect of reduced voltage and current on motor losses and power factor, (2) a comparison of motor operation with and without the PFC in line, (3) suggested revisions and modifications to the original design, and (4) energy savings attributable to the PFC. Auburn tested five low horsepower motors, four of which were three phase (Table 1).

Table 1

Low Horsepower Motors Tested in Auburn Study

| Name | Horsepower | Voltage | RPM | Phase |
|---|---|---|---|---|
| Pacer | 5 | 208,220/240 | 3445 | 3 |
| Wagner | 3 | 220 | 1750 | 3 |
| Pacer | 3 | 220 | 1750 | 3 |
| General Electric | 1 | 220/445 | 1140 | 3 |
| Century | 1.5 | NA | 3450 | 1 |

The data for the Auburn study was gathered in five stages.

1. Rated voltage test--each motor was tested at its rated voltage while the torque was varied from full load to no load (Figure 5).

2. Constant torque test--each motor maintained a constant shaft torque while the supply voltage was reduced until the motor almost stalled (Figures 6 through 10).

3. Constant voltage/constant power factor--a variac was used to maintain a constant power factor while the shaft torque was varied from full load to no load (Figure 11).

4. Constant voltage/Auburn design test--an Auburn-designed device was applied while the shaft torque was varied from full load to no load (Figure 12).

[4]Russell and Lowry.

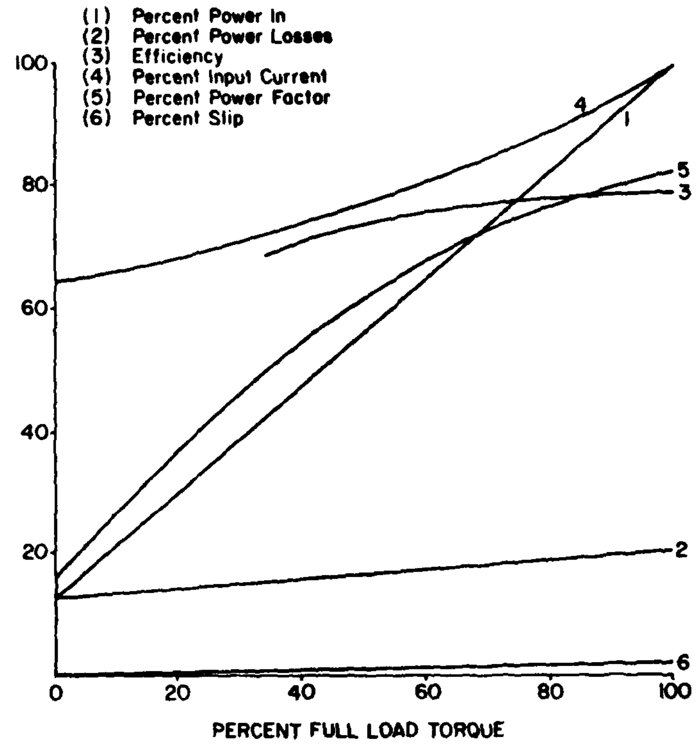


Figure 5. Auburn rated voltage test for 5-hp Pacer (Louis Allis).

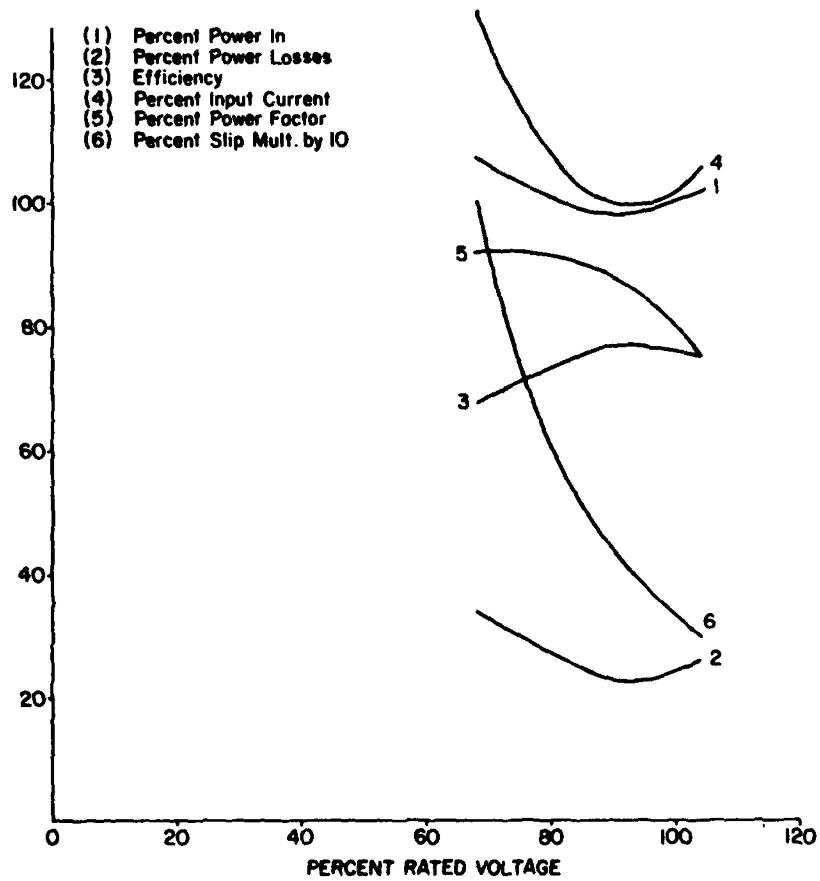


Figure 6. Auburn constant torque test for 5-hp Pacer (100 percent torque).

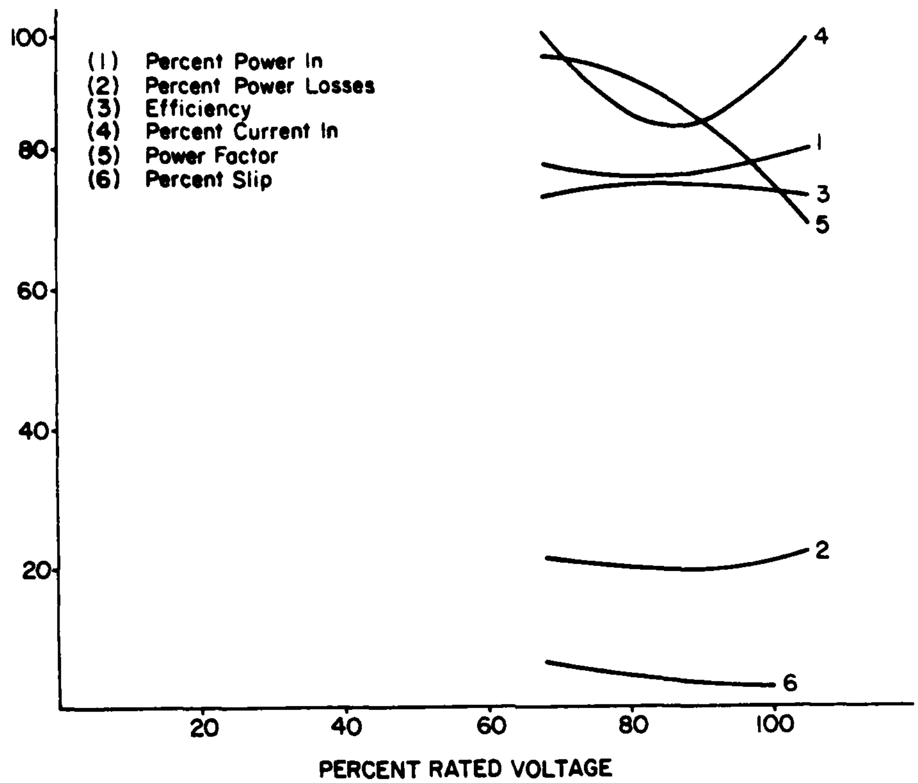


Figure 7. Auburn constant torque for 5-hp Pacer (75 percent torque).

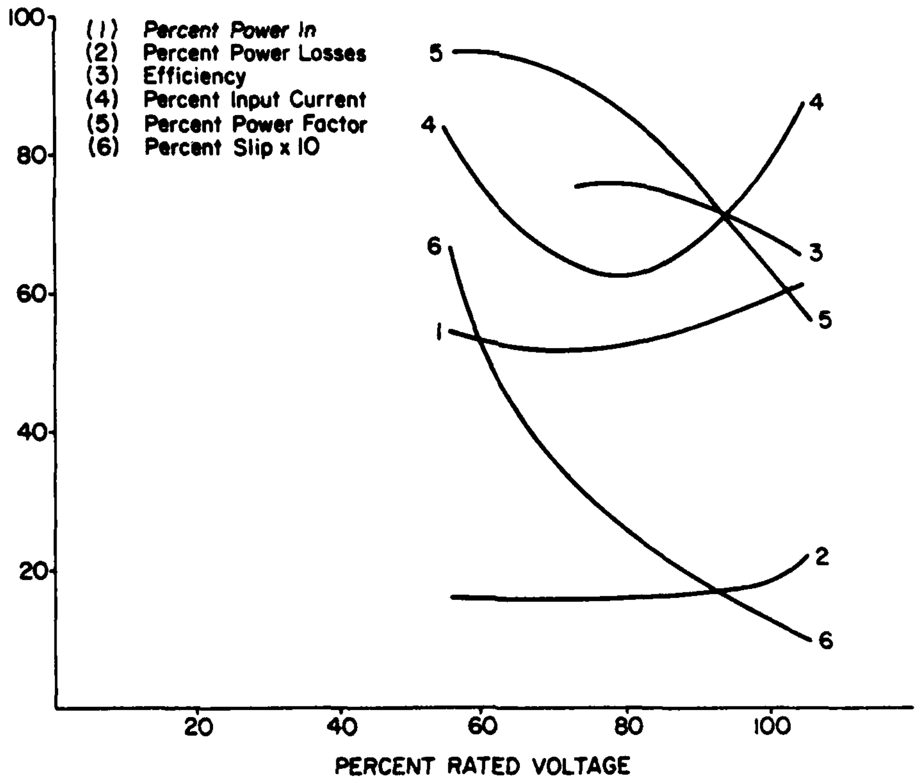


Figure 8. Auburn constant torque test for 5-hp Pacer (50 percent torque).

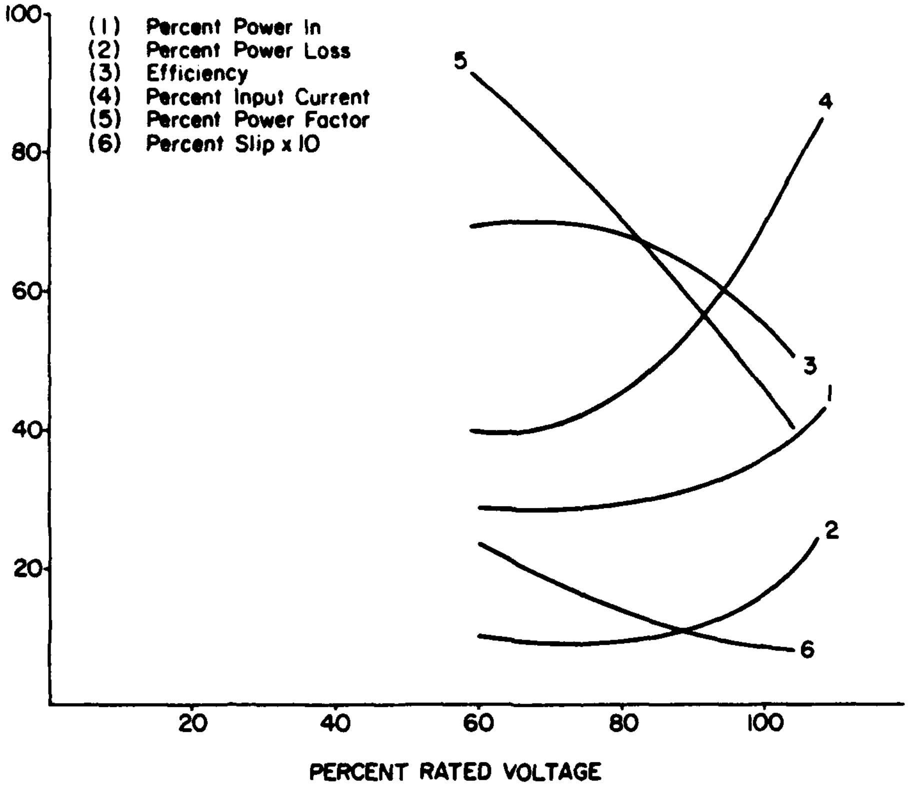


Figure 9. Auburn constant torque test for 5-hp Pacer (25 percent load).

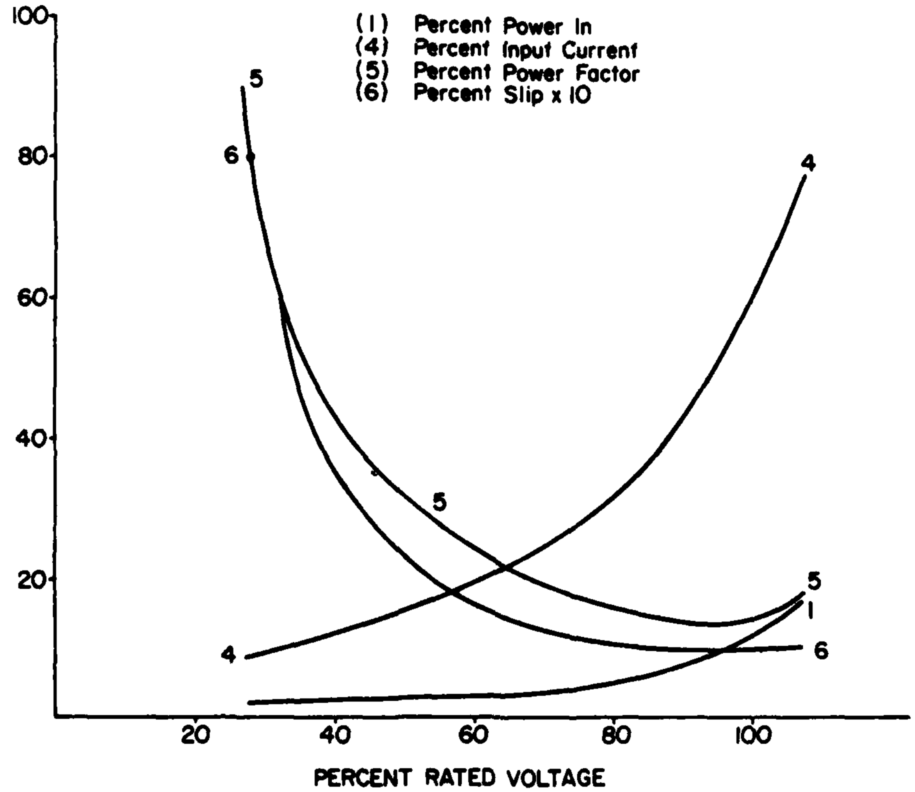


Figure 10. Auburn constant torque for 5-hp Pacer (no load).

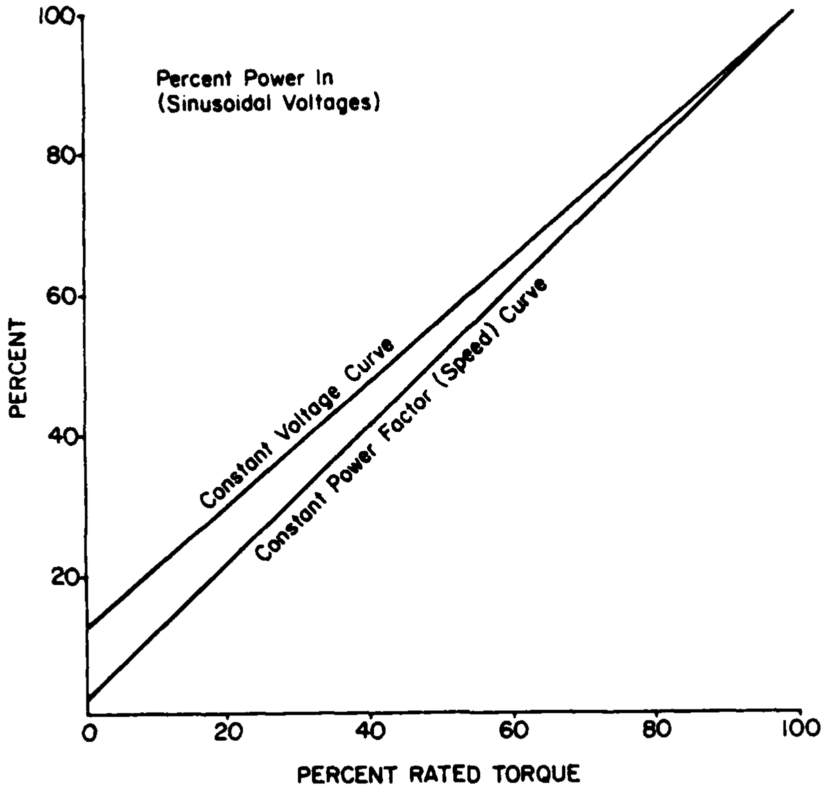


Figure 11. Constant voltage/constant power factor test.

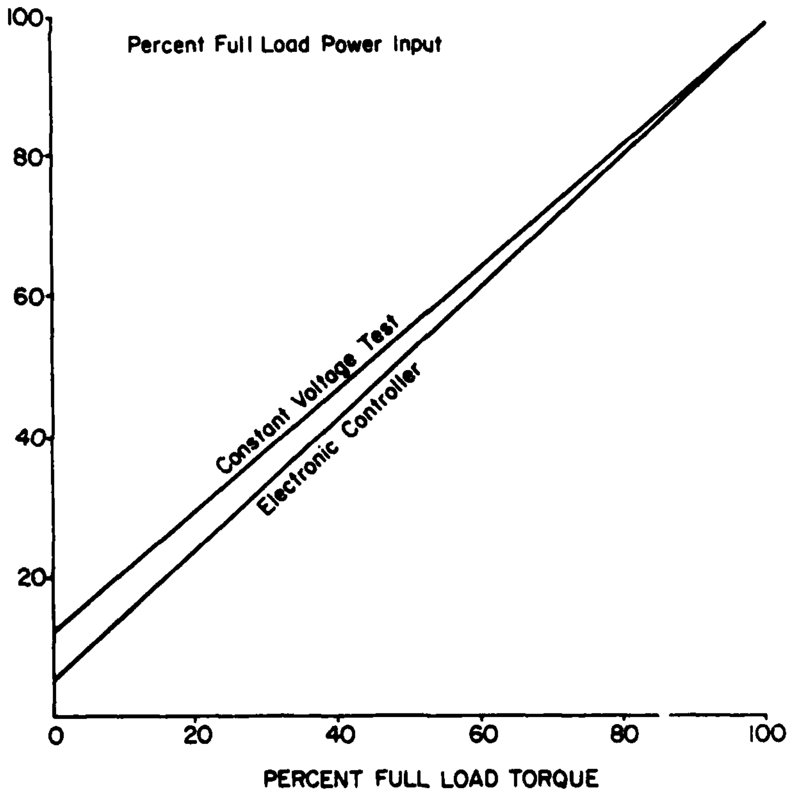


Figure 12. Constant voltage/electronic controller test.

5. Input power reduction test--the three-phase motors were tested with the NASA device in line while the shaft torque was varied from full load to no load (Figure 12).

The rated voltage test (Figure 5) demonstrated that motor efficiency and power factor decrease as torque decreases. During the constant torque tests, the power consumption and losses decreased and the motor efficiency and power factor increased as voltage input decreased. The most dramatic improvement in motor operation was for an applied torque of less than 50 percent of full load, which is demonstrated by comparing Figures 8 and 9.

Figure 11 was developed from data obtained by maintaining a constant voltage input and a constant motor power factor. The difference between the two lines is equal to percent power reduction realized. As torque decreases, greater power savings result. An indication of power savings resulting from a voltage-controlling device similar to the PFC is given in Figure 12. As load decreases, the PFC becomes most effective, reducing power losses by as much as 40 percent (Figure 13).

Data for each of the five motors tested is provided in Tables 2 through 6. In each case, the heading "Active" is with the PFC in line and "Shorted" is with the PFC removed from the circuit. As load requirements decrease, the ability to reduce power consumption improves. Comparing different motors emphasizes that the effect of the initial-design PFC varies with specific motors -- but in each instance a savings can be realized.

The testing revealed some problems with the PFC design. One problem in the three-phase design was the misfiring of the triacs, which was caused by phase shift induced in the timing by the control circuitry. To correct this problem, capacitors were added in the control circuit to bring the timing in line. Another problem was in grounding each of the phase voltages. This was corrected by establishing a common neutral for each phase of the PFC.

After testing and modifying the NASA PFC, the Auburn study concluded that energy savings could be realized. Lightly loaded motors showed the greatest power savings, and maximum savings at no load ranged from 20 percent to 74 percent for motors tested. In the opinion of the researchers, the PFC offered "...a valuable technique for reducing energy consumption of induction motors which operate for significant periods of time at no load or light loads."[5]

The Auburn report is useful in that it documents probable energy savings associated with an electronic voltage controlling device. However, the study did not investigate possible problem areas associated with PFC operation, such as induced line harmonics, rotor speed stability, the ability to pick up a clutched load, the effect of harmonics on the motor, and protection of the device and motor should stalling occur. Neither does it include any field tests on industrial equipment nor mention any applications for PFC use.

The report does offer the following equation for calculating energy savings from use of a PFC, which allows the engineer to determine if the PFC

[5]Russell and Lowry, p 50.

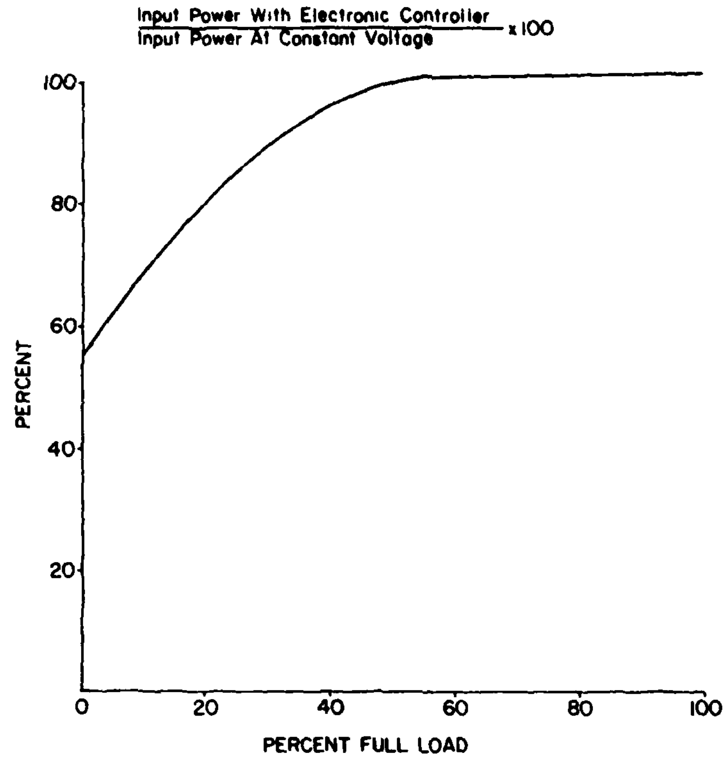


Figure 13. Input power reduction with electronic controller.

Table 2

Electronic Controller/Constant Voltage Test Data for
5 Hp, 3 $\phi$, 220 V, 3445 RPM, Pacer (Louis Allis)
Induction Motor

| Electronic Controller | Line Voltage (volts) | Line Current (amps) | Input Power (watts) | Torque (in.-ib) | Speed (rpm) |
|---|---|---|---|---|---|
| Active | 220 | 19.2 | 6486 | 123 | 3410 |
| Shorted | | | | | |
| Active | | 15 | 4746 | 92 | 3459 |
| Shorted* | | 15 | 4793 | 92 | 3470 |
| Active | | 11.6 | 3288 | 62 | 3503 |
| Shorted | | 12.0 | 3306 | 62 | 3517 |
| Active | | 11.6 | 1752 | 31 | 3546 |
| Shorted | | 9.9 | 1902 | 31 | 3560 |
| Active | | 5.76 | 324 | 0 | 3596 |
| Shorted | | 9.42 | 594 | 0 | 3596 |

*Base Data

Table 3

Electronic Controller/Constant Voltage Test Data for
3 Hp, 3 $\phi$, 220/440 V, 1750 RPM, Wagner Induction Motor

| Electronic Controller | Line Voltage (volts) | Line Current (amps) | Input Power (watts) | Torque (in.-lb) | Speed (rpm) |
|---|---|---|---|---|---|
| Active | 220 | 10.9 | 3552 | 108 | 1724 |
| Shorted* | | 10.7 | 3534 | 107 | 1728 |
| Active | | 8.49 | 2670 | 81 | 1745 |
| Shorted | | 8.46 | 2652 | 81 | 1748 |
| Active | | 6.08 | 1782 | 54 | 1764 |
| Shorted | | 6.09 | 1800 | 54 | 1767 |
| Active | | 4.35 | 876 | 27 | 1782 |
| Shorted | | 4.38 | 930 | 27 | 1784 |
| Active | | 3.03 | 90 | 0 | 1798 |
| Shorted | | 3.75 | 132 | 0 | 1799 |

*Base Data

Table 4

Electronic Controller/Constant Voltage Test Data for
3 Hp, 3 $\phi$ , 220 V, 1750 RPM, Pacer (Louis Allis)
Induction Motor

| Electronic Controller | Line Voltage (volts) | Line Current (amps) | Input Power (watts) | Torque (in.-lb) | Speed (rpm) |
|---|---|---|---|---|---|
| Active | 220 | 10.22 | 2826 | 109 | 1744 |
| Shorted* | | 10.1 | 2922 | 1109 | 1746 |
| Active | | 8.61 | 1962 | 73 | 1758 |
| Shorted | | 8.91 | 2076 | 73 | 1764 |
| Active | | 7.59 | 1122 | 36 | 1770 |
| Shorted | | 7.80 | 1278 | 36 | 1782 |
| Active | | 3.9 | 132 | 0 | 1798 |
| Shorted | | 7.71 | 515 | 0 | 1798 |

*Base Data

Table 5

Electronic Controller/Constant Voltage Test Data for
1 Hp, 3 $\phi$ , 220 V, 1140 RPM, G.E. Induction Motor

| Electronic Controller | Line Voltage (volts) | Line Current (amps) | Input Power (watts) | Torque (in.-lb) | Speed (rpm) |
|---|---|---|---|---|---|
| Active | 220 | 3.19 | 939 | 55 | 1156 |
| Shorted* | | 3.19 | 939 | 55 | 1156 |
| Active | | 2.97 | 843 | 49 | 1159 |
| Shorted | | 2.96 | 843 | 49 | 1162 |
| Active | | 2.47 | 609 | 34 | 1174 |
| Shorted | | 2.51 | 617 | 34 | 1173 |
| Active | | 2.03 | 356 | 18 | 1182 |
| Shorted | | 2.12 | 367 | 18 | 1186 |
| Active | | 1.55 | 83 | 0 | 1197 |
| Shorted | | 1.97 | 113 | 0 | 1198 |

*Base Data

Table 6

Manual Electronic Controller/Constant Voltage Test Data for
1.5 Hp, 1 $\phi$ , 220 V, 3450 RPM, Century
Induction Motor

| Electronic Controller | Line Voltage (volts) | Line Current (amps) | Input Power (watts) | Torque (in.-lb) | Speed (rpm) |
|---|---|---|---|---|---|
| Active | 220 | 8.3 | 1584 | 27 | 3463 |
| Shorted* | | 8.28 | 1576 | 27 | 3465 |
| Active | | 6.86 | 1232 | 20 | 3496 |
| Shorted* | | 6.78 | 1224 | 20 | 3501 |
| Active | | 5.54 | 896 | 14 | 3526 |
| Shorted | | 5.46 | 896 | 14 | 3533 |
| Active | | 4.36 | 564 | 7 | 3554 |
| Shorted | | 4.42 | 576 | 7 | 3562 |
| Active | | 3.16 | 220 | 0 | 3581 |
| Shorted | | 3.86 | 284 | 0 | 3581 |

*Base Data

is suitable for a given application. The only requirement is that the engineer must know the motor duty cycle.

$$\text{kwh savings/year} = (T_{NL}\Delta P_{NL} + T_{PL}\Delta P_{PL})(\frac{T_{op}}{10^5}) \qquad \text{[Eq 2]}$$

where $T_{NL}$ = operating time at no load in percent of total operating time per year

$\Delta P_{NL}$ = power savings at no load in watts = input power with rated voltages minus input power with PFC

$T_{PL}$ = operating time at partial load in percent of total operating time per year

$\Delta P_{PL}$ = power savings at partial load in watts = input power with rated voltages minus input power with PFC

$T_{op}$ = total operating time of motor per year in hours.

## Pacific Gas and Electric Study

The California utility, Pacific Gas and Electric Company (PG+E), did a study to determine if NASA-designed PFCs save energy.[6] Its secondary objectives were to evaluate the performance and observe operating characteristics of the device under transient loads and full load starting. The PFCs tested were:

1. Power Saver: Power Saver International Limited, Christchurch, New Zealand

2. Power Mate: KF Industries, Inc., Philadelphia, PA

3. Vectrol: Vectrol Inc., Oldsmar, FL

4. Modified Vectrol: Vectrol Inc., Oldsmar, FL.

Each of the tested PFCs was brought up to operating temperature and thermal stability was maintained. Motor load was varied in incremental steps from 0 percent to 125 percent of motor full load rating. The Vectrol controller was also tested under transient and full load starting conditions. The data obtained were curve-fitted with a second-order polynomial regression of several dependent variables: electrical power input, average rms line current, motor stator voltage with Vectrol controller, and total harmonic volt amperes appearing on line side of Vectrol controller. Table 7 provides a list of test equipment, and wiring diagrams are displayed in Figure 14.

[6] Wallace N. Beaty, Evaluation of Four Nola Type, Three Phase, 25-30 HP Electronic Motor Voltage Controllers, Report 911.7-81.5 (Pacific and Electric Company, 1980).

Table 7

PG&E Test Equipment List

1. KF Industries Model 21-2S, 30 hp, 480 V, Three Phase NASA Voltage Controller,"Power Mate," Serial No. 814005.
2. Power Saver International Limited 25 hp, 480 V, Three Phase NASA Voltage Controller, "Power Saver."
3. Vectrol Model 60ES1-4025E, 25 hp, 480 V, Three Phase NASA Voltage Controller, "Modified Vectrol," Serial No. 014.
4. Vectrol Model 60ES1-4025EB, 25 hp, 480 V, Three Phase NASA Voltage Controller, "Modified Vectrol," Serial No. 014.
5. General Electric Model 5K284AL205C, 25 hp, 480 V, NEMA Design B-DP, Three Phase Induction Motor.
6. Go Power Systems Model 356B, Water Brake Dynamometer, Serial No. CH 2145.
7. Scientific Columbus Model SC-10 Watthour Standard, Serial Nos. 0005336 and 0005327.
8. Honeywell Model 906B, Oscillograph, Serial No. 9-8785.
9. Shimpo Model DT-301 Digital Strobe, Serial No. 06055507.
10. Tektronix Model 7623 Oscilloscope.
11. Beckman Model 3060 and 3030 Digital Multimeters.
12. Hewlett Packard Model 3580A Spectrum Analyzer, Serial No. 2030A04856.
13. Hewlett Packard Model 9835A Computer.

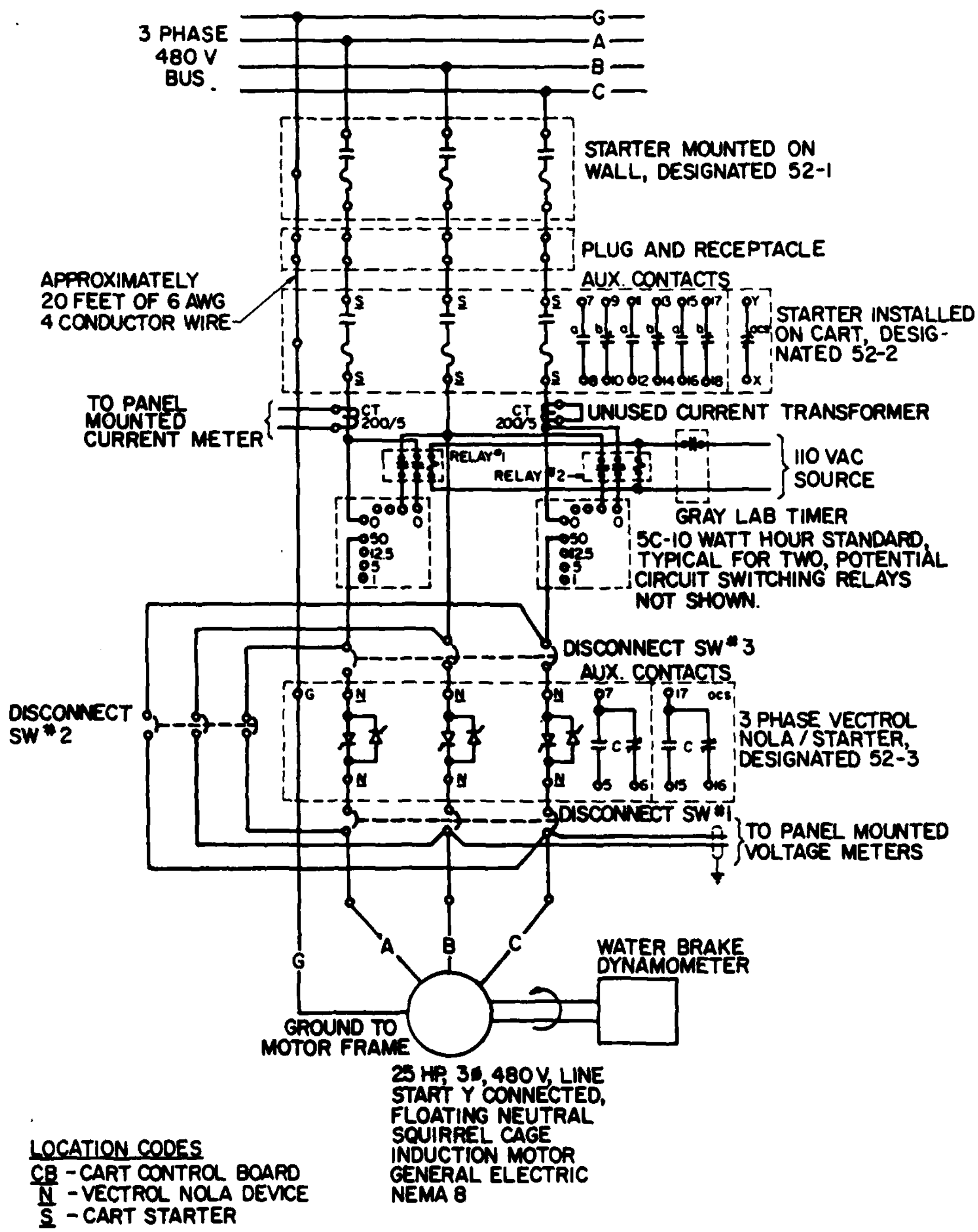


Figure 14. Wiring diagram for PG&E study.

After the initial operation of the PFCs, the first three listed were found to be unstable in the voltage they supplied. Maximum fluctuations of 60 V rms per 1-second interval were recorded. The instability was minimized but not eliminated by varying the device's maximum voltage control. Marginally stable operation was achieved by increasing the rms voltage from 400 to 440 V at a 10 percent load. However, 2 to 3 percent voltage fluctuations still occurred, causing motor torque pulsations which were observed visually with a stroboscope. At this point, three of the PFCs were eliminated from the test, leaving only the modified Vectrol unit.

Further testing of the modified Vectrol PFC showed the following results. At no-load operation a 60 percent power savings was realized, a 10 percent load resulted in a 10 percent power reduction; and at 100 percent load an increase of 2 percent power consumption was found. Stator voltage was stable when the load varied from full to no load. Monitoring the line current revealed that at 25 percent load, there was no current and no power reduction. The line voltage and current harmonics were monitored so the total harmonic volt-amperes (VA) as a function of load could be determined. The modified Vectrol device caused harmonic VA to decrease by 60 percent at full load. However, harmonics were not reduced until the load was increased to 64.5 percent of rated full load. The worst case of harmonics occurred at 20 percent load for a 45 percent increase. This information is summarized in Table 8; Figures 15 through 18 display the graphic results.

Testing the PFC transient response was limited by the dynamometer response time of 2 seconds. It is possible that quicker load variations may cause the motor-PFC combination to stall or operate in an unstable manner. Over a 2-second time span, the load was changed from 10 percent to 100 percent, causing the line voltage to increase from 242 volts to 466 volts.

The Vectrol "soft start" feature, which reduces current surge, was also tested by PG&E. Oscillograms are provided in Figures 19 through 21. The Vectrol unit reduced current surge by 30 percent with full motor load applied. For an 8 percent load, surge current dropped off 19 percent.

Table 8

Modified Vectrol Test Results

| | Load | | |
|---|---|---|---|
| | 0% | 10% | 100% |
| % Power Reduction | +60% | +10% | -2% |
| Stator Voltage | 190 V | 235 V | 425 V |
| Line Current Reduction | +72% | +22% | -8% |
| Total Harmonic Reduction | -30% | -40% | +60% |

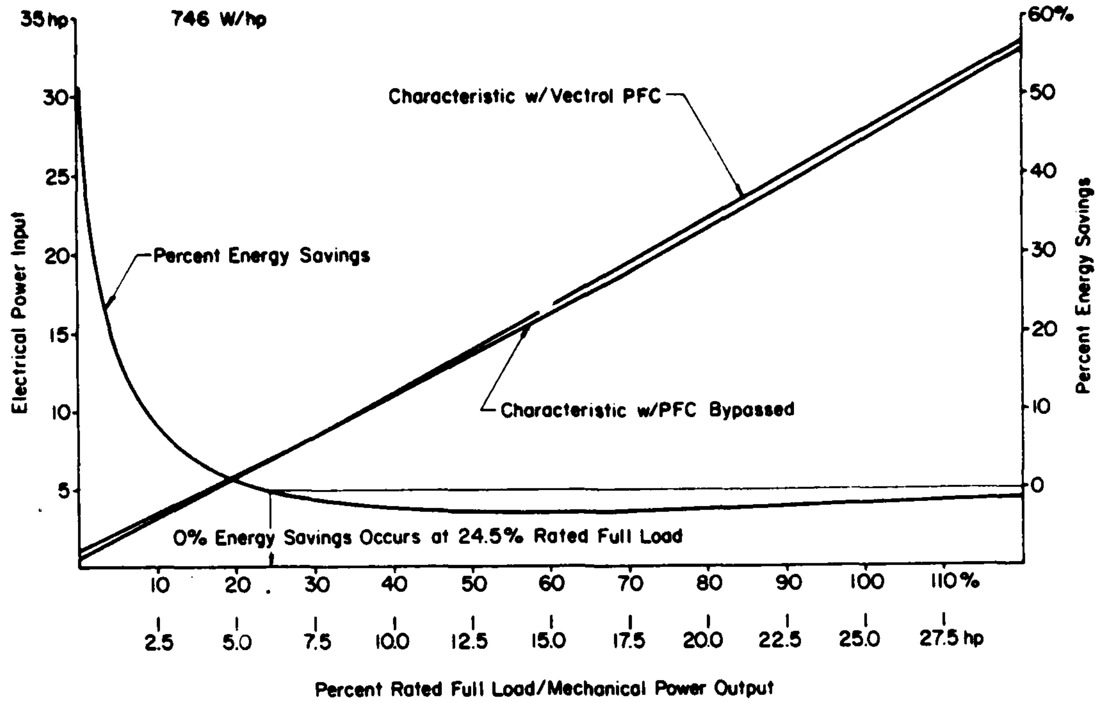


Figure 15. Electrical power input and percent energy saving as a function of percent rated full load for the Vectrol PFC and bypassed operation.

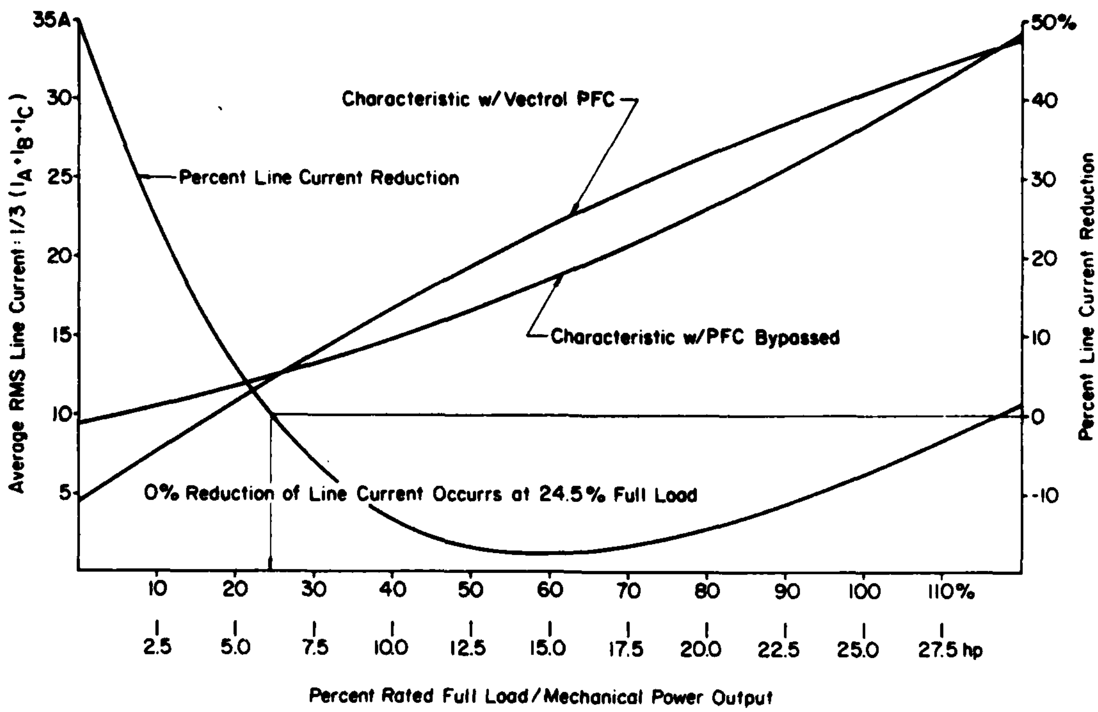


Figure 16. Average line current and percent current reduction as a function of percent rated full load for the Vectrol PFC and bypassed operation

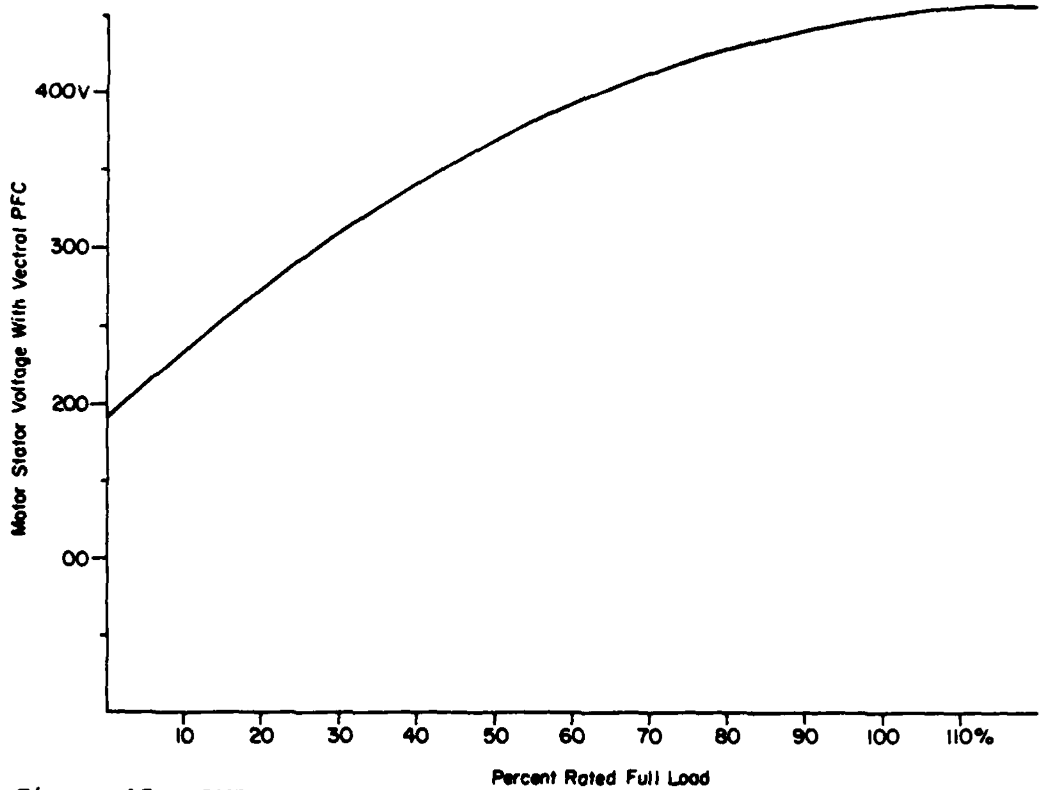


Figure 17. RMS motor stator voltage as a function of percent rated load for operation with the Vectrol PFC.

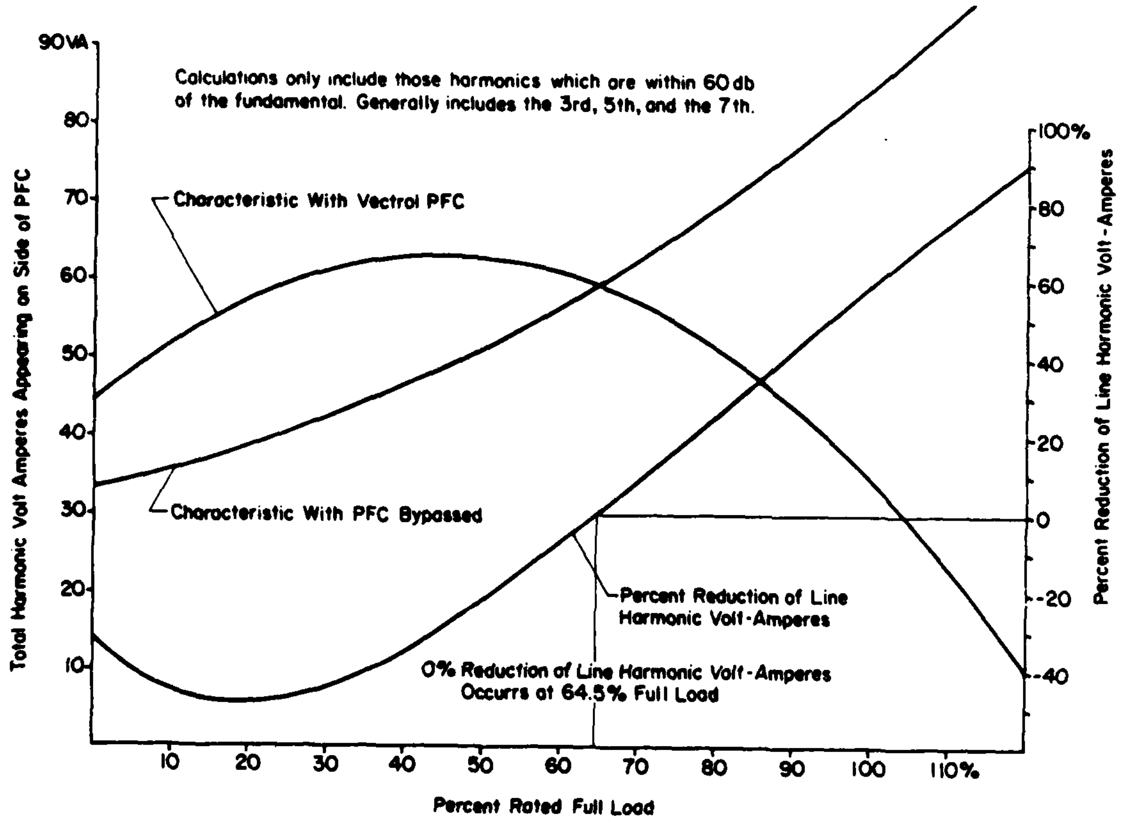


Figure 18. Total line harmonic volt-amperes and percent reduction as a function of percent rated load for the Vectrol PFC and bypassed operation.

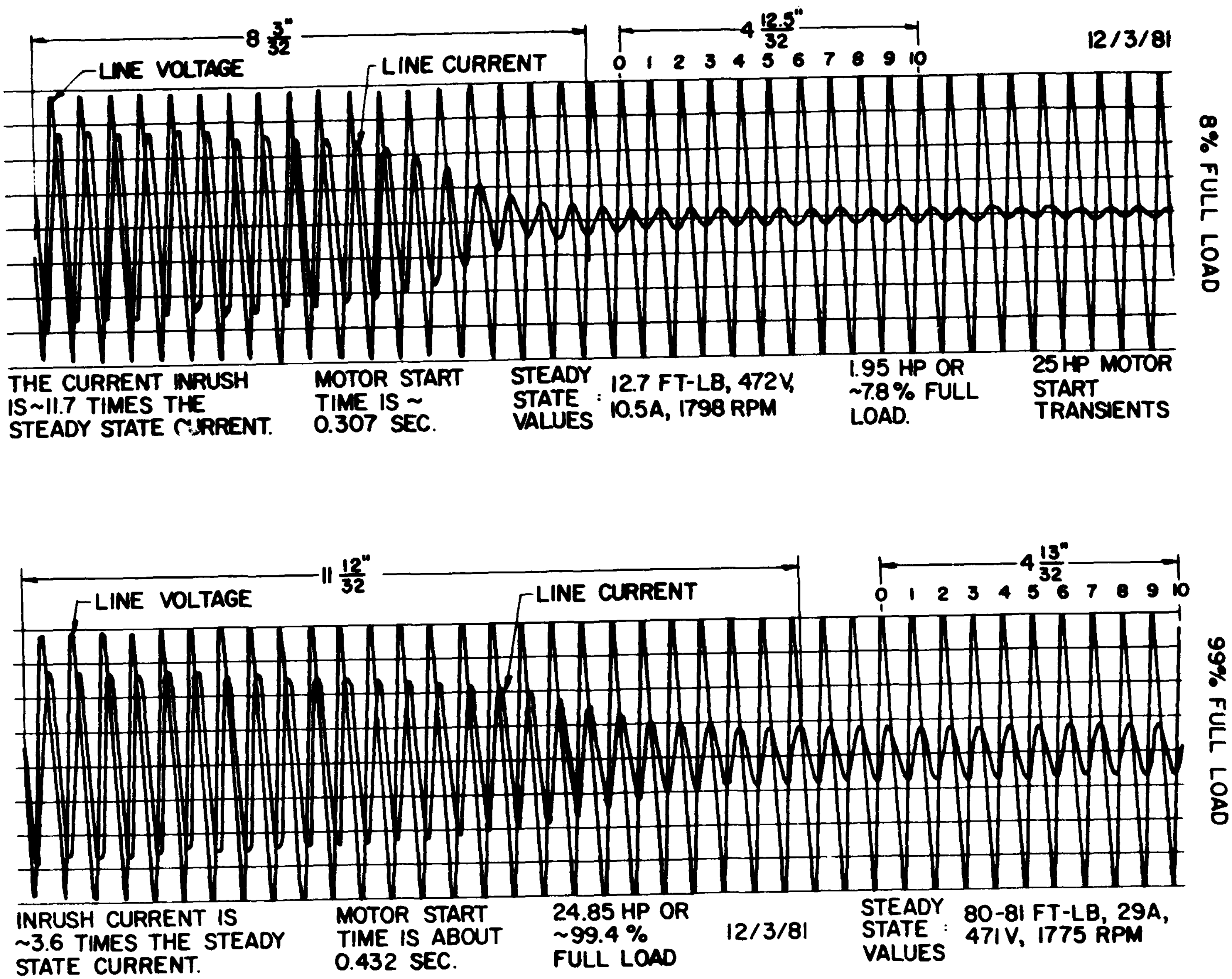


Figure 19. Transient voltage and current oscillograms of motor starting with the modified Vectrol bypassed 8 percent and 99 percent rated full load.

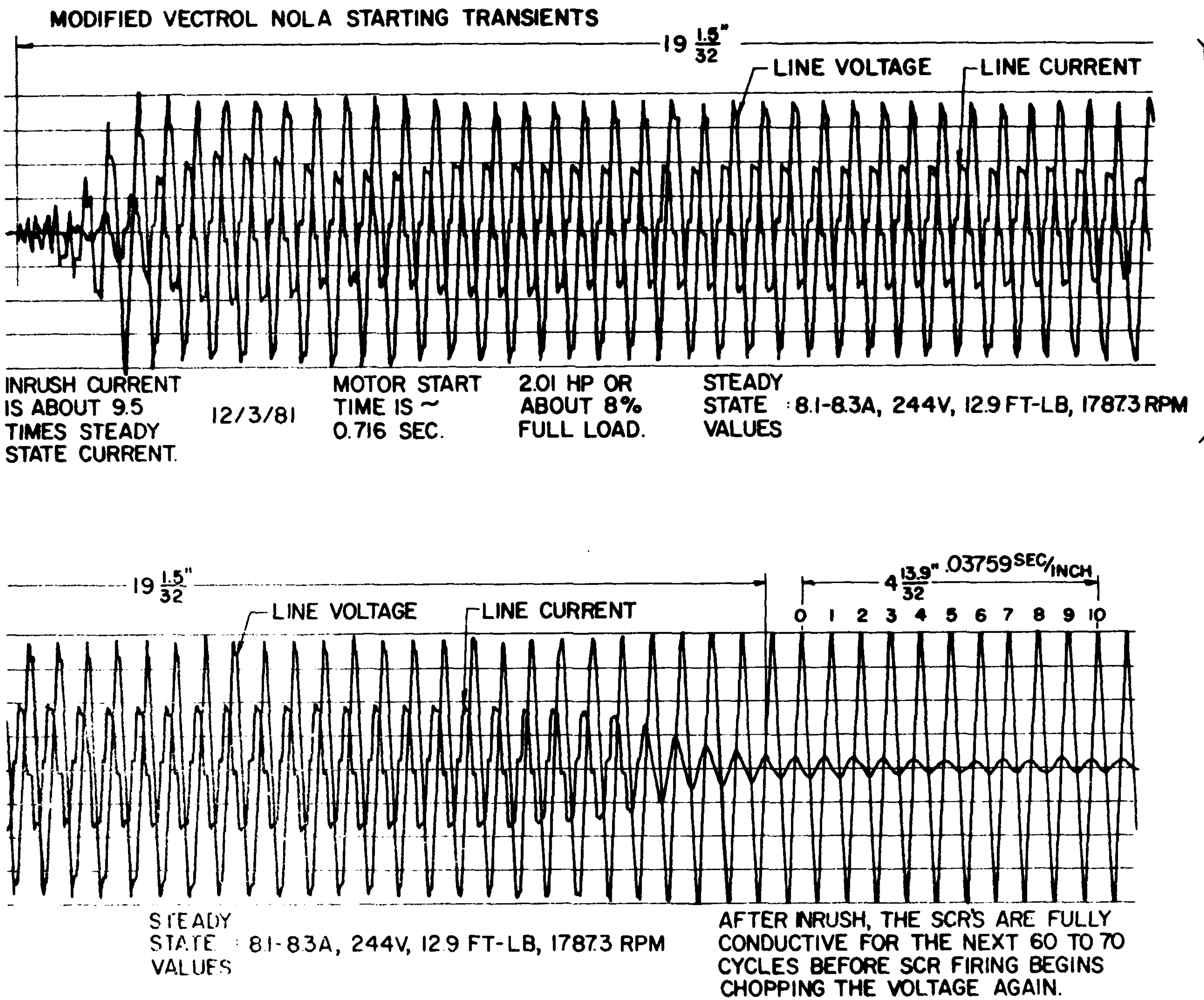


Figure 20. Transient voltage and current oscillogram, part 2.

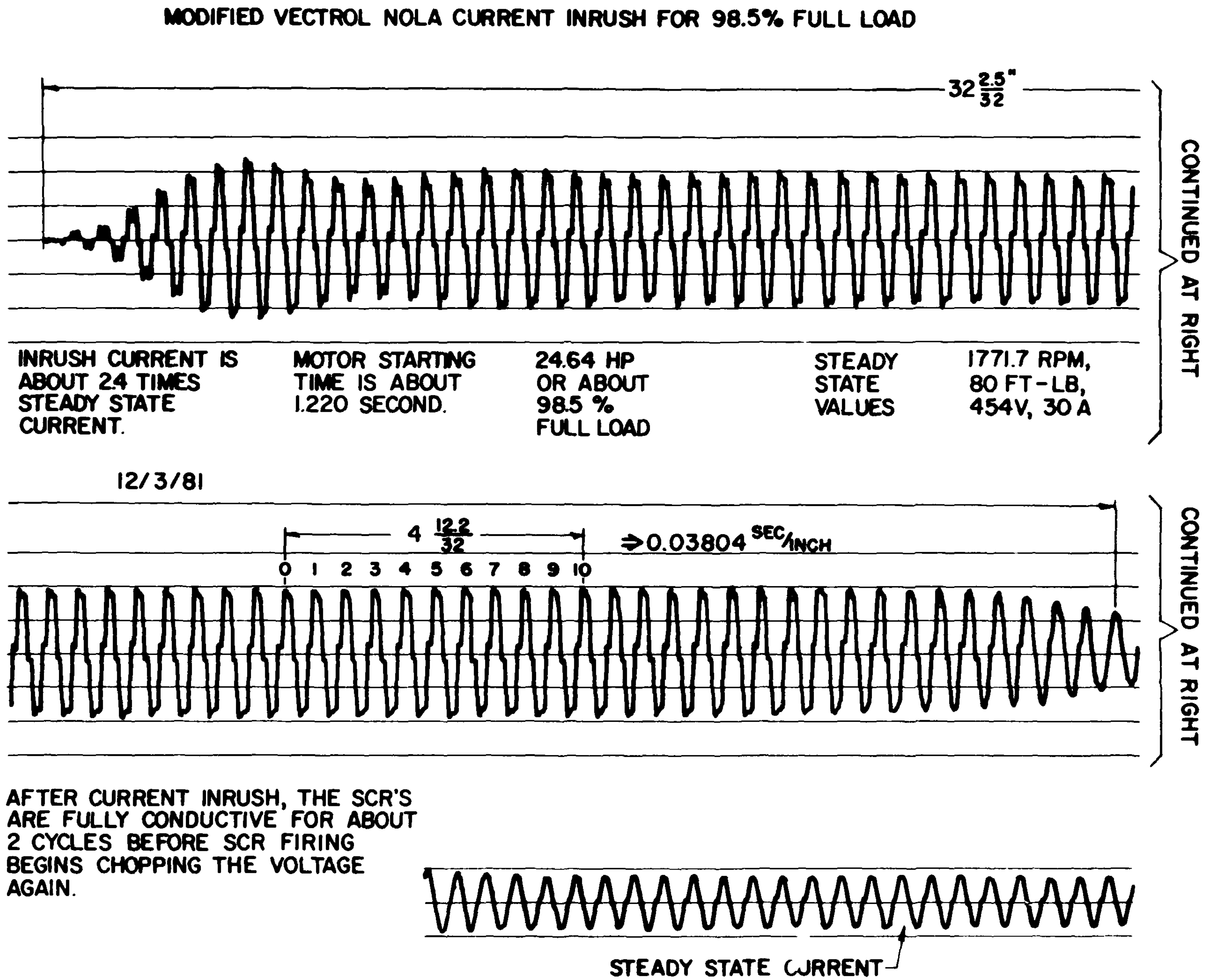


Figure 21. Transient voltage and current oscillogram, part 3.

In summary, the modified Vectrol PFC reduces energy consumption for light loads; however, power consumption increases beyond a 25 percent load. PG&E also specifies that savings will not be as great if the PFC is operated with an energy-efficient motor. Though the unmodified Vectrol, Power Mate, and Power Saver could not be set for stable operation with a 25-hp General Electric motor, they might be compatible with other motors. The Vectrol PFC reduced motor skin temperature below loads of 25 percent, but an indication as to the actual temperatures was not reported.

The PG&E study did not cover economic payback or how to size the PFC to a particular application.

## San Diego Gas and Electric Study

SDG&E's testing was primarily to determine the effect the NASA PFC has on power consumption and power factor over a range of motorloads.[7] The PFC tested was a Scott & Fetzer Co. Motor Energy Controller (MEC), model MEC 4020. The motor, a General Electric 2 hp, three-phase, 460V, 3.1 amp induction motor, was mechanically loaded with a "Go Power" water brake dynamometer. The power input and output were monitored throughout the test with the PFC in and out of the test circuit. During testing, motor input voltage was held at a constant 480 V. Figures 22 and 23 display SDG&E's test results. Additionally, SDG&E monitored motor temperature and noted a drop from 132°F to 122°F, due to the presence of the PFC.

The data in Table 9 can be broken down into two categories, mechanical load and electrical power input. In comparing the data in the table, the most important information is in the "% load" and "Watts" rows. Varying the load from 100 percent full load to a 2 percent load, the greatest power reduction occurs at the minimum motor shaft load. This is to be expected as it is the operating principle of the PFC. Note that at full load operation, the PFC increases power consumption above the reference mode. This is because of power losses inherent to the PFC itself. Looking at the volt-amp reactive power consumed (VARS), a few trends are apparent. Without the PFC in line, VAR flow is relatively constant; as shaft load drops off, VAR flow increases slightly, about 4 percent. Conversely, with the PFC in line, VAR flow drops off significantly. This is also reflected in the VA (volt-amp) readings. From the drop in VAR flow, a similar improvement in power factor is anticipated; the best case improvement was 23 percent. The VAR improvement was 33 percent. Although both the watts and VARS decrease significantly, the power factor improvement is not as great because of relationships between these terms as shown by Equations 3 and 4.

$$VA = \sqrt{\text{watts}^2 + \text{VARS}^2} \qquad \text{[Eq 3]}$$

$$\%PF = \frac{\text{watts}}{VA} \times 100\% \qquad \text{[Eq 4]}$$

[7] G. B. Humphrey, R. A. Magdaluyo, and J. D. Huey, Three Phase Power Factor Controller Test (Internal Correspondence)(San Diego Gas and Electric Company, December 1981).

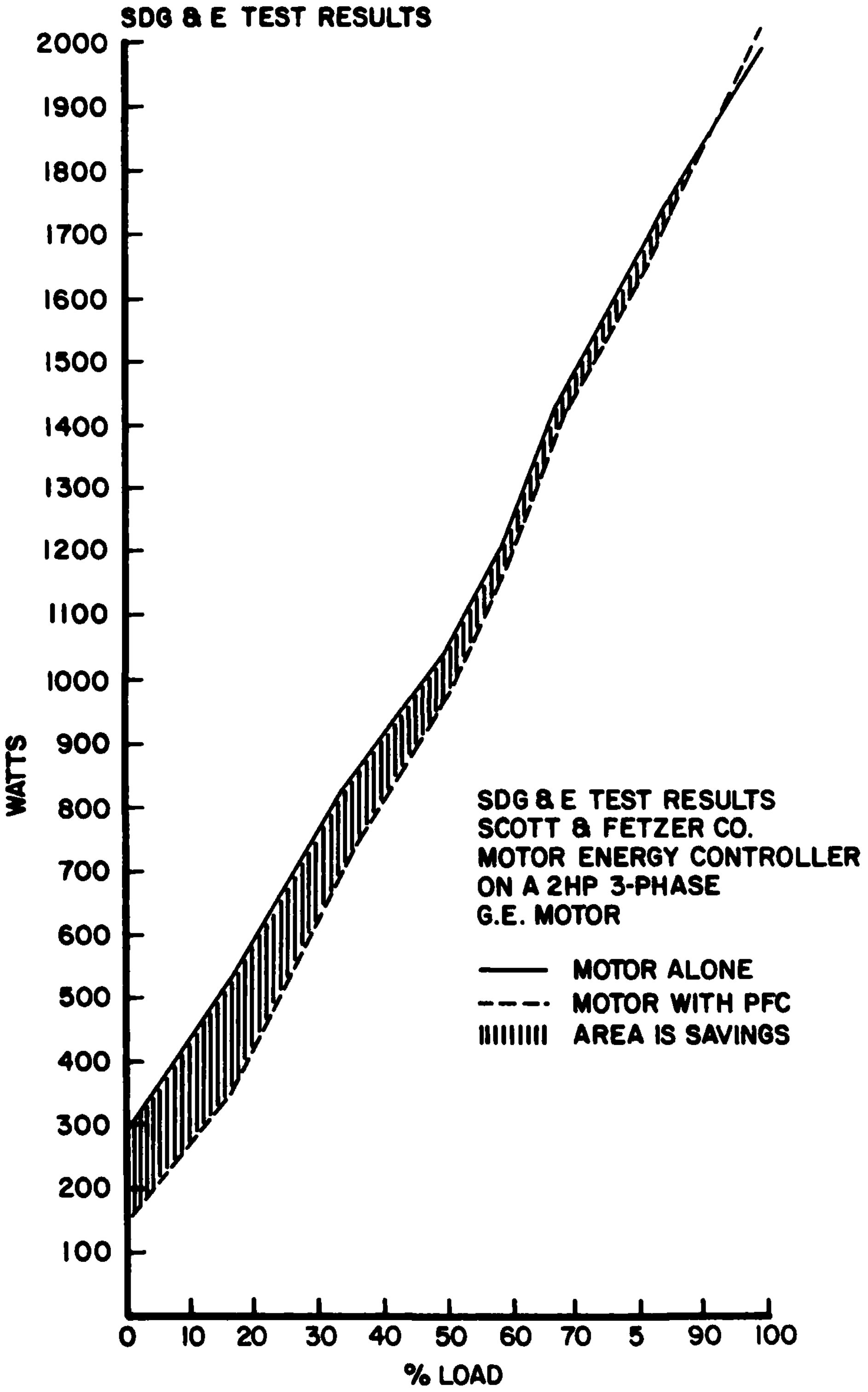


Figure 22. SDG&E test results.

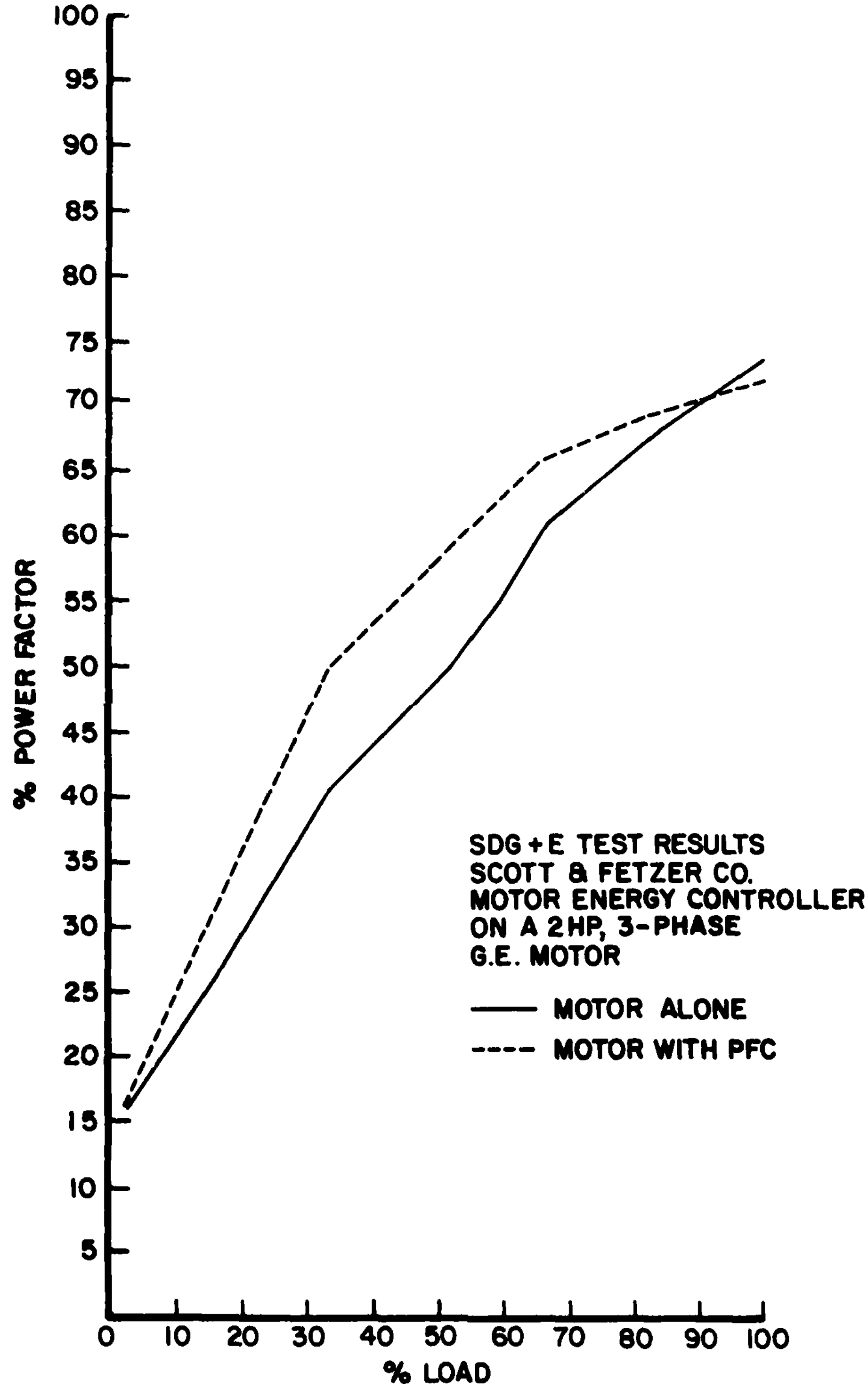


Figure 23. SDC&E test results.

Table 9

SDG&E Test Results

Test Data

Without Power Factor Controller

| Test # | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Torque (ft-lb) | 6.0 | 5.0 | 4.C | 3.5 | 3.0 | 2.0 | 1.0 | .1 |
| rpm 1760 | 1760 | 1760 | 1760 | 1760 | 1760 | 1760 | 1760 | |
| Horsepower | 2.01 | 1.68 | 1.34 | 1.17 | 1.00 | .67 | .33 | .03 |
| % Load | 100.6 | 83.8 | 67.0 | 58.7 | 50.3 | 33.5 | 16.8 | 1.7 |
| Watts | 1984 | 1720 | 1420 | 1200 | 1040 | 824 | 528 | 312 |
| VARS 1856 | 1848 | 1848 | 1840 | 1840 | 1864 | 1904 | 1936 | |
| VA 2717 | 2525 | 23341 | 2197 | 2114 | 2038 | 1976 | 1961 | |
| Percent Power Factor | 73.0 | 68.1 | 60.9 | 54.6 | 49.2 | 40.4 | 26.7 | 15.9 |

With Power Factor Controller

| Test # | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Torque (ft-lb) | 6.0 | 5.0 | 4.0 | 3.5 | 3.0 | 2.0 | 1.0 | .1 |
| rpm 1740 | 1740 | 1740 | 1740 | 1740 | 1740 | 1740 | 1740 | |
| Horsepower | 1.99 | 1.66 | 1.33 | 1.16 | .99 | .66 | .33 | .03 |
| % Load | 99.4 | 82.3 | 66.3 | 58.0 | 49.7 | 33.1 | 16.6 | 1.7 |
| Watts | 2000 | 1656 | 1360 | 1144 | 968 | 680 | 344 | 160 |
| VARS 1936 | 1736 | 1560 | 1440 | 1352 | 1184 | 1024 | 960 | |
| VA 2784 | 2399 | 2070 | 1839 | 1663 | 1365 | 1080 | 973 | |
| Percent Power Factor | 71.8 | 69.0 | 65.7 | 62.2 | 58.2 | 49.8 | 31.9 | 16.4 |
| Watt % Change | +.8 | -3.7 | -4.2 | -4.7 | -6.9 | -17.5 | -34.8 | -48.7 |
| PF % Change | -1.6 | +1.3 | +7.9 | +13.9 | +18.3 | +23.3 | +19.5 | +3.1 |

Comparison of Line and Motor Voltage with PFC

| | | | | |
|---|---|---|---|---|
| Percent Load | 100 | 75 | 50 | 33 |
| Input Voltage | 480 | 480 | 480 | 480 |
| Motor Voltage | 404 | 496 | 384 | 377 |

Once the data were gathered, SDG&E used polynomial regression techniques to analyze PFC characteristics. Equations relating power consumption and power factor to motor load were generated using polynomial regression. The following regression models resulted, where X is the percent load on the motor:

$$P_{REF} = 280.73437 + 14.76462X + 0.02927X^2 \quad \text{[Eq 5]}$$

$$P_{FCC} = 104.08936 + 16.34015X + 0.02927X^2 \quad \text{[Eq 6]}$$

$$PF_{REF} = 13.92807 + 0.85549X - 0.026X^2 \quad \text{[Eq 7]}$$

$$PF_{PFC} = 14.67419 + 1.19582X - 0.0634X^2 \quad \text{[Eq 8]}$$

Equations 5 and 7 represent motor operation without the PFC while Equations 6 and 8 are with the PFC in line. Error analysis outlined in the report found maximum percent error to be as follows for the data generated by polynomial regression:

$P_{REF} = \pm 13.3$ percent
$P_{PFC} = \pm 30.7$ percent
$PF_{REF} = \pm 7.8$ percent
$PF_{PFC} = \pm 9.5$ percent

The worst-case error for each parameter occurred at no-load operation of the motor. Figures 24 and 25 display graphs of power consumption with respect to motor load and power factor with respect to motor load using the regression equation shown above.

Each graph has two lines plotted showing results with and without the controller. The power savings at a particular load can be determined from Figures 22 and 24 by taking the difference between the two lines. Note that as the load approaches 80 percent of full load, no power savings occur and at approximately 90 percent load, the power consumption is greater with the PFC in line. This is due to power losses in the PFC which are dissipated in the form of heat. Obviously, best results are obtained for motor loads less than 50 percent. Figures 23 and 25 indicate the power factor improvement associated with the PFC. At both no load and full load the improvement in power factor is quite small. However, loads in the range of 30 percent to 75 percent offer an improvement in power factor from 23 percent to 51 percent, respectively.

Using the results of their analysis, SDG&E estimated annual power savings associated with the PFC. This data is based on the assumption that motor operation is at a constant load. From this information, SDG&E calculated a simple payback based on a cost of $0.10/kWh, and a $160 purchase price for the PFC. The results are shown in Table 10.

In general, the analysis of the Scott & Fetzer MEC is quite thorough. Power savings and power factor improvement were recognized and good correlation existed throughout the analysis. Also, motor temperature was briefly

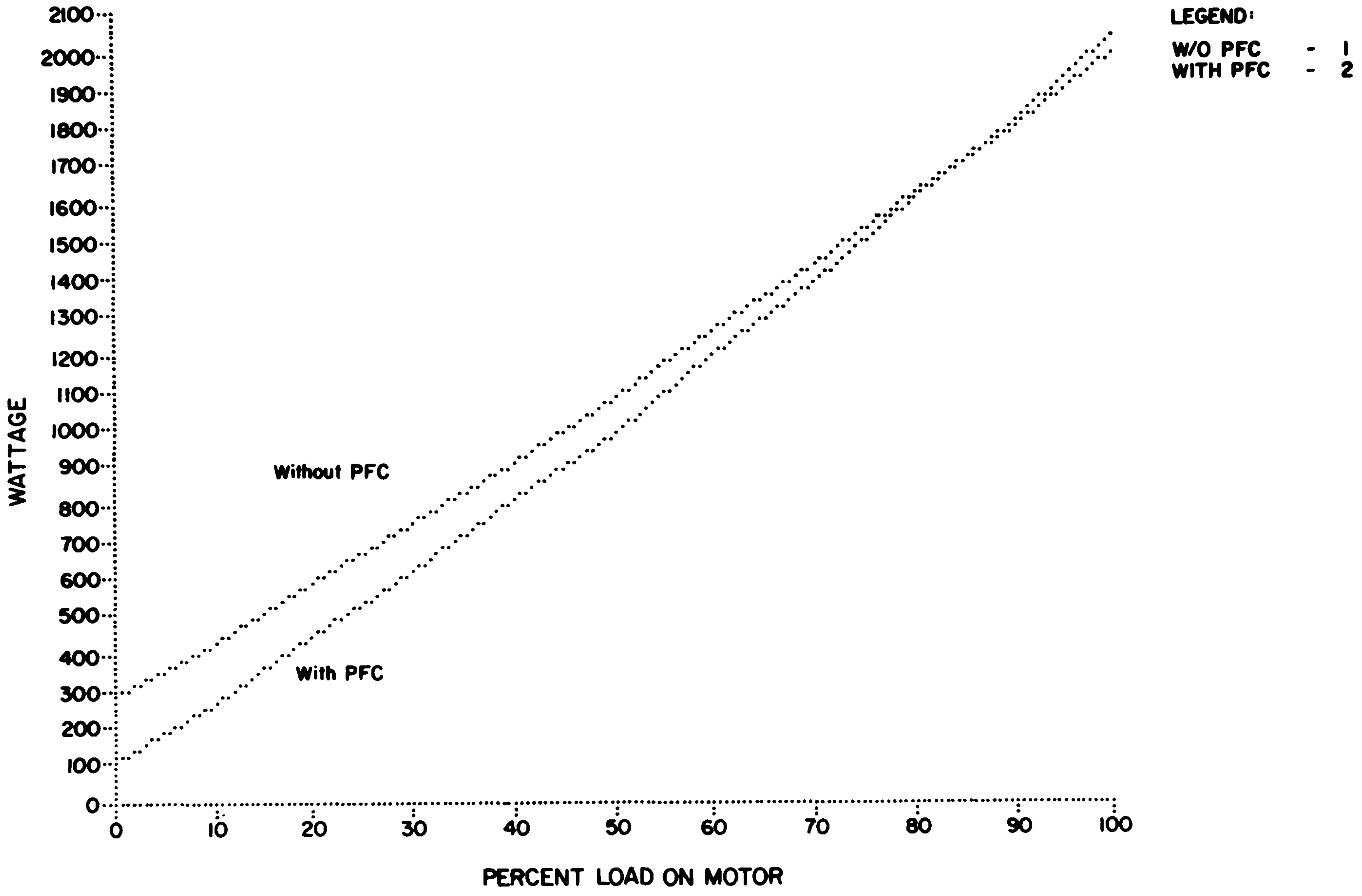


Figure 24. Power consumption vs motor load.

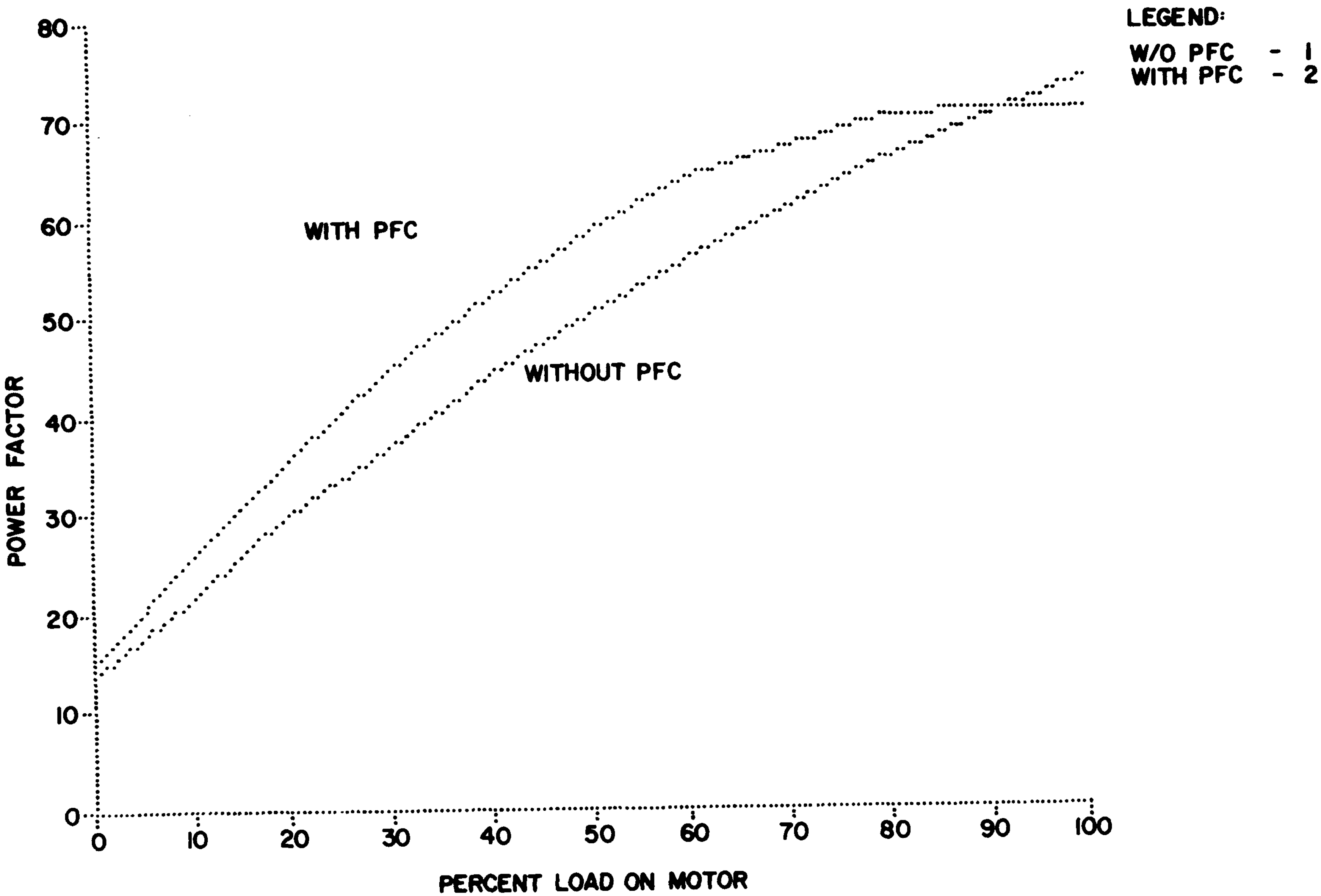


Figure 25. Power factor vs motor load.

Table 10

Economic Analysis

Kilowatt-Hour Savings With
Power Factor Controller

| Annual Operating Hours | 2920 | 4380 | 5840 | 8760 |
|---|---|---|---|---|
| Percent Motor Load | | | | |
| 0 | 516 | 774 | 1031 | 1547 |
| 10 | 468 | 703 | 937 | 1405 |
| 20 | 418 | 626 | 835 | 1253 |
| 30 | 364 | 546 | 728 | 1091 |
| 40 | 307 | 460 | 613 | 920 |
| 50 | 246 | 370 | 493 | 739 |
| 60 | 183 | 275 | 367 | 550 |
| 70 | 117 | 175 | 234 | 250 |
| 80 | 47 | 71 | 95 | 142 |
| 90 | -25 | -38 | -51 | -76 |
| 100 | -101 | -152 | -203 | -304 |

Simple Payback in Months*

| Annual Operating Hours | 2920 | 4380 | 5840 | 8760 |
|---|---|---|---|---|
| Percent Motor Load | | | | |
| 0 | 37.2 | 24.8 | 18.6 | 12.4 |
| 20 | 45.9 | 30.7 | 23.0 | 15.3 |
| 50 | 78.0 | 51.9 | 38.9 | 26.0 |
| 70 | 164.1 | 109.7 | 82.1 | 54.9 |

* At $0.10/kWh and $160 for PFC purchase.

considered and found to decrease with the use of the MEC. The graphs by SDC&E give a quick indication of potential improvements with PFC operation. One area not covered which would be most helpful is an analysis of the motor speed stability. SDC&E did not do any field testing or offer any suggestions to industrial applications.

## Northern Natural Gas Study

The Northern Natural Gas Company (NNG) conducted an in-house study on PFCs to determine if they meet manufacturer's claims, what NNG equipment is best suited for PFC interface, and how the PFC can be incorporated into the NNG system.[8]

Initial analysis indicated that though the PFC could be used with any induction motor, the power savings were greatest with light- and variable-loaded motors. Applications specifically considered were air compressors, pumps, fin fans, a bench grinder, a bench brush, and a typewriter. Engineers at NNG concluded from their tests that the PFC was best suited for water pumps, especially engine jacket water pumps and process solvent circulating pumps. Table 11 outlines the motor type and associated power savings.

The NNG engineering staff also fild tested a PFC applied to a 40-hp bilge pump motor. Pump load was varied by restricting flow at the discharge valve, allowing head and flow rate to be controlled. Figure 26 shows how power

Table 11

Field Measured Energy Saving

| Motor Data | % Energy Saving | % Full Load Point |
|---|---|---|
| 5 hp, 220 V, 3 phase Sump pump | 6 | 90 |
| 10 hp, 480 V, 3 phase Fin Fan | 5 | 88 |
| 1/3 hp, 110 V, 1 phase bench grinder-no load | 43 | 70 |
| 1/4 hp, 110 V, 1 phase bench wire brush-no load | 33 | 68 |
| Typewriter-essentially no load | 60 | 69 |

[8]William E. Frasier, Electric Motor Energy Consumption Control (Northern Natural Gas Company, October 1981).

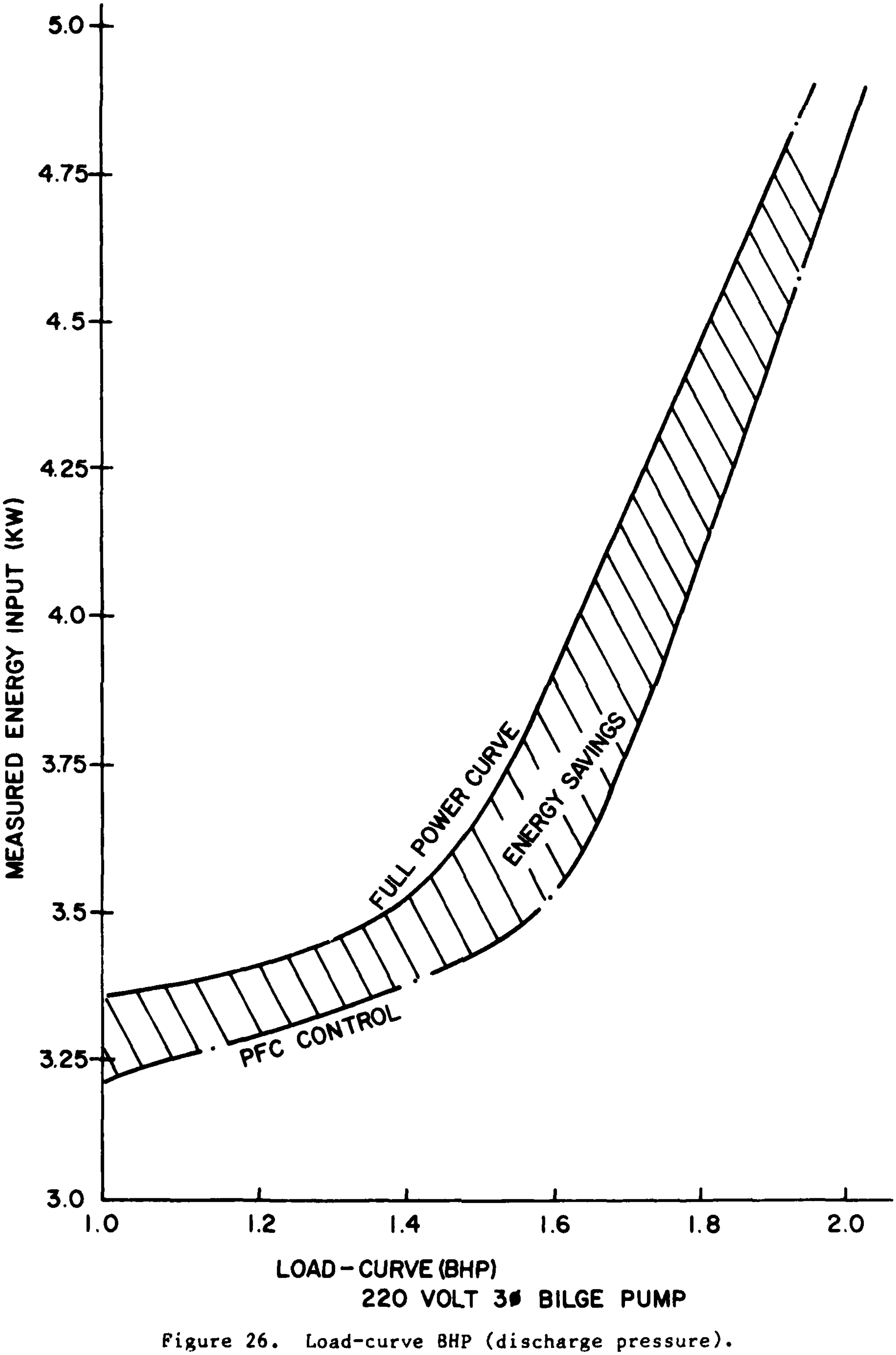


Figure 26. Load-curve BHP (discharge pressure).

consumption varies with load in this particular test. The difference between the full power curve and PFC control curve equals the energy savings resulting from the PFC. Figure 27 shows anticipated power savings with a PFC over a range of motor loads. NNG claims typical savings to be between 5 percent and 40 percent depending on the motor, and specifies 5 percent to 10 percent savings to be used in prediction of savings with any motor.

After completing field testing, NNG did an economic analysis of PFC installations. The cost of purchasing and installing a 480 V, three-phase 40-hp PFC was found to be $860 in 1981. On a bilge pump, the payback is 8 years. This payback period is large because the pump operates only 4 hours a day. If the duty cycle were 90 percent, payback would be less than 1 year. For NNG's generalized model, payback on a PFC for a 480 V 10-hp motor with 5 percent energy savings would be about 1 year.

The NNG report concluded that PFCs are a good investment when applied to motors with a long duty cycle at partial load.

## Municipal Electricity Department Study (New Zealand)

The Municipal Electricity Department (MED) of Christchurch, New Zealand, conducted tests of PFC model PS3075 manufactured by Power Saver International, Limited.[9] The research covered three areas. Of primary concern to MED was harmonics generated by the operation of the PFC; next was to determine if the PFC acted as a power factor correction device; and finally to determine if the PFC actually saved energy.

In analyzing PFC harmonics, a range of loads was applied to the motor with and without the PFC connected. A Plessy Selective Audio Frequency Power System Analyzer monitored harmonic content in the line. Since the New Zealand power system operates at 50 Hz, all harmonics will be integer multiples of 50. The motor tested was a 10-hp GEC Kapak Induction Motor type D132 M. Name plate data were as follows: 7.5 kW, three-phase, 400 V, 50 Hz, Class B, 1440 rpm. The results of the harmonics test are provided in Table 12. The numbers are maximum harmonic currents; no load was specified, nor was it clear if these currents are for one particular load.

From their harmonic testing, MED concluded "...it has been determined that the NASA power saver will not contribute a disproportionate amount of harmonic interference." MED was most concerned with their carrier signals on the transmission system at frequencies of 590 Hz and 710 Hz. They surmised that because the significant portion of sizable harmonics occurs below 550 Hz, interference problems would not result. Also, because harmonics due to the PFC were less than those at motor slip frequencies, 538 Hz and 840 Hz, they present no problem. MED made this assumption because the power system sustained the harmonics at slip frequencies without problems and could

[9] J. G. Hodge, Report on Tests Carried Out to Ascertain the Suitability of the Three-Phase NASA Power Saver Unit for Connection to the Christchurch MED Distribution System (Municipal Electricity Department of Christchurch, New Zealand, December 1981).

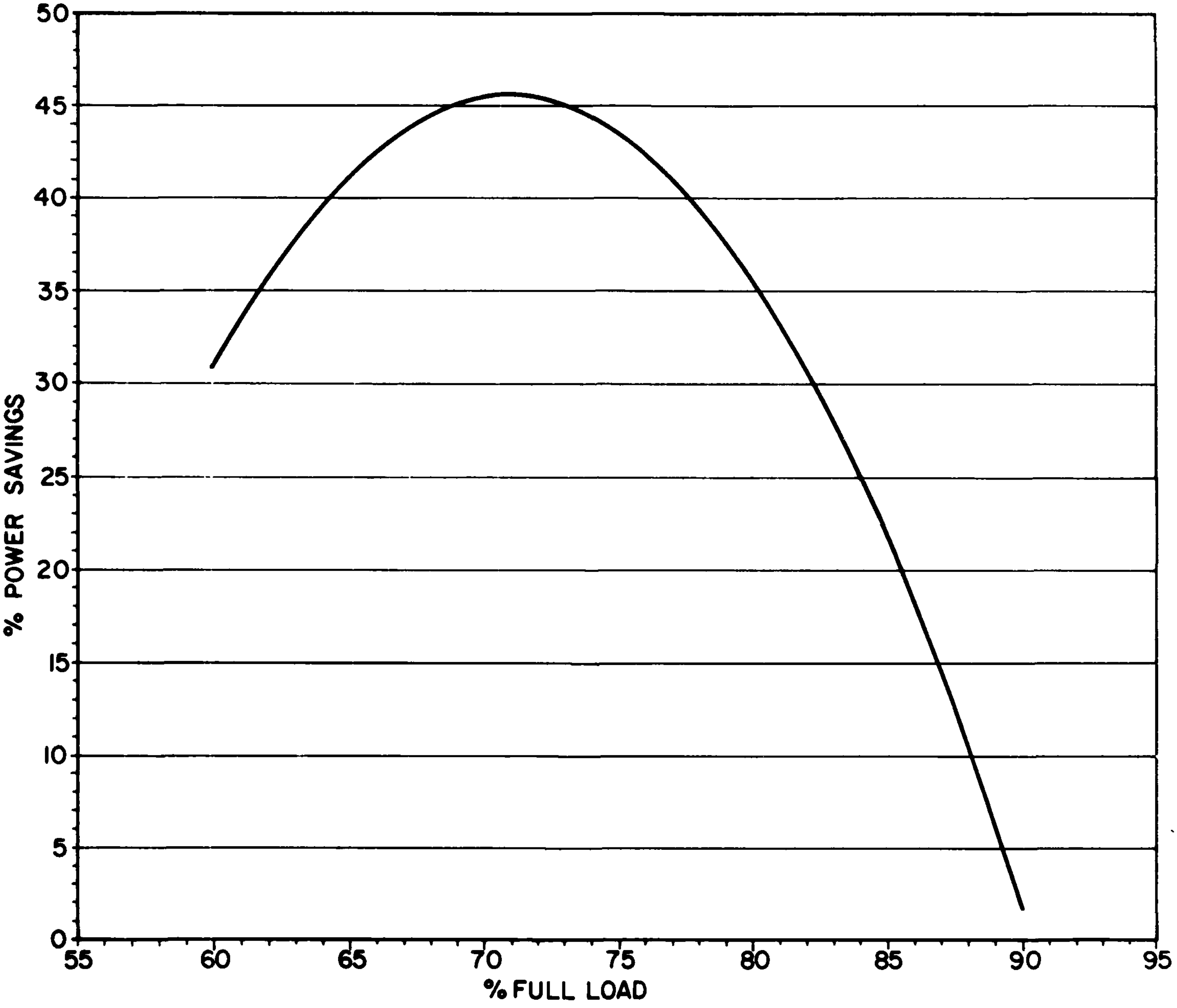


Figure 27. Northern Natural Gas theoretically derived power savings vs percent full load.

Table 12

Maximum Harmonic Currents,
10-hp Kapak Induction Motor

| Frequency (Hz) | Harmonic Order | Power Saver Harmonic Current (Amps) | Motor Only Harmonic Current (Amps) |
|---|---|---|---|
| 100 | 2 | 0.6 | |
| 150 | 3 | 0.4 | 0.3 |
| 200 | 4 | 0.4 | |
| 250 | 5 | 1.2 | 0.4 |
| 300 | 6 | 0.15 | |
| 350 | 7 | 0.6 | |
| 450 | 9 | 0.05 | |
| 550 | 11 | 0.1 | |
| 650 | 13 | 0.05 | |
| Slip 538 | | 0.4 | 0.4 |
| Slip 840 | | 0.3 | 0.3 |

therefore deal with the other harmonics as long as they were not considerably greater.

The second test, power factor correction, showed a slight improvement with the PFC in line as demonstrated in Table 13. The power factor was measured by using the Plessy Selective Audio Frequency Power System Analyzer and a phase angle meter. MED concluded that, however slight, a power factor correction was realized. They commented that the PFC's function was energy conservation and that a common misconception was to expect significant power factor correction.

The final portion of MED's investigation determined power savings. A Sangamo induction type watt-hour meter was used to facilitate this test. MED's findings were that 50 to 70 percent of the "possible energy savings" were actually saved with the PFC. The "possible energy savings" were defined by using a variac to lower the applied voltage and thus locate the best operating points for the motor at a series of different loads.

Table 13

Power Factor

| | |
|---|---|
| No load, without PFC | 0.24 |
| No load, with PFC | 0.31 |
| Full load, with or without PFC | 0.81 |

The MED study results do not make it clear if the increased harmonics are insignificant. It would be helpful to see plots of harmonics generated with the PFC in line with specific loads applied to the motor. One conclusion that can be drawn from the MED report, however, is that PFC-induced harmonics present no problems for transmission line carrier signals. MED established that a slight power factor correction did occur and that some power savings were realized.

## Nordic Controls Study

Nordic Controls Co., a PFC manufacturer, has provided test results from motors used in machining.[10] Their test compares line voltage, line current, and power consumption with and without the PFC in line. They did not list the PFC model used or specifications associated with it. Savings are computed in terms of kWh and dollars. Dollar savings are based on a 16-hr day, 260 day per year motor operation, with the cost of electricity at $.05 per kWh. The calculated dollar savings and return on investment does not take into account the following: reduced air-conditioning costs, effect of increased voltage on the second shift, power factor correction, high voltage protection, effect of the soft start feature, and tax credits.

Table 14 displays Nordic's results. This test is helpful in that it gives applications of the PFC and typical savings, but information concerning chassis temperature, length of testing, reactive power consumption, and power factor is not given. This information is necessary to determine all of the actual benefits incurred.

## Control Development, Inc. Study

A series of PFC tests has been provided to CERL by Charles Popp of Control Development, Inc., a PFC distributor. Popp has assembled a portable demonstration and test unit which is used to take measurements within a manufacturing facility. The advantage of this type of test is that actual machine operations are tested instead of the motor/dynamometer combination found in a research environment. These tests show the potential savings offered by a PFC. Also, they can be used to compare different installations of the PFC and thereby determine the appropriateness of a particular application.

[10] Neal Engineering Sales Co., Study on Nordic Controls Co. 1 and 3 Phase PFCs (September 1980).

Table 14

PFC Savings Study, Nordic Controls Co.

| Application | Volts | Amps | kWh | PFC Cost ($) | Energy Savings ($) | Payback (months) | Return on Investment (%) |
|---|---|---|---|---|---|---|---|
| Plastic Scrap Granulator | | | | | | | |
| Motor Type: U.S. 286 T Frame 30 hp, 230/460 Volt, 1750 rpm, 78/39 Amp | | | | | | | |
| Line | 475 | 19 | 5.0 | | | | |
| PFC | 300 | 8 | 2.4 | 820.00 | 540.80 | 18 | 66.0 |
| Surface Grinder | | | | | | | |
| Motor Type: U.S. 245 T Frame 15 hp, 230/460 Volt, 1750 rpm | | | | | | | |
| Line | 230 | 12 | 2.8 | | | | |
| PFC | 160 | 7.5 | 1.2 | 772.00 | 332.80 | 28 | 42.9 |
| Air Compressor | | | | | | | |
| Motor Type: Siemens 286 TSD 40 hp, 220/460 Volt, 3535 rpm, 104/52 Amp | | | | | | | |
| Line | 475 | 35 | 26.8 | | | | |
| PFC | 440 | 35 | 25.6 | 820.00 | 249.60 | 40 | 30.4 |
| Gisholt Turret Lathe | | | | | | | |
| Motor Type: Westinghouse 324 T Frame, 40 hp, 230/460 Volt, 1750 rpm | | | | | | | |
| Line | 461 | 32.2 | 14.4 | | | | |
| PFC | 350 | 22.1 | 9.6 | 820.00 | 998.40 | 10 | 121.0 |

When discussing the potential of a PFC, Control Development specifies motor characteristics which are best suited for interfacing with a PFC. Generally, ideal operating characteristics are:

1. Lightly loaded motors.

2. Motors with intermittent loads.

3. "T" frame motors.

4. Motors that run hot.

5. Motors that operate more than one shift daily.

6. Rewound motors.

7. Motors with over-voltage conditions.

8. Facilities with high demand charges or power factor penalties.

Control Development's test consists of monitoring line voltage, line current, and kWh hour consumption. Testing was done without the PFC in line and then with the device added. The results from five different companies are compiled in Table 15.

On the test sheets, Control Development cites a return on investment and a payback period. These are calculated as follows:

$$\text{Payback period} = \frac{\text{Controller Cost}}{\text{Power Savings}} \qquad \text{[Eq 9]}$$

$$\text{Return on Investment} = \frac{\text{Savings}}{\text{Net Investment}} \qquad \text{[Eq 10]}$$

The tests are useful in that typical savings were determined and various applications compared. One drawback of this type of testing, however, is that it is oriented to power savings only. Chassis temperature, reactive power dissipation, and power factor would also be helpful information. Also, these tests were conducted over a short period, hours vs weeks, and thus only give a fair indication as to possible savings attributable to the PFC.

Southeast Energy Management Corporation Study

Sav-A-Stop, a firm that operates convenience food stores, contracted Southeast Energy Management Corporation (SEMCO) to conduct a study on power factor controllers for use in their warehouse.[11] SEMCO monitored motor power consumption, power factor, and motor skin temperature, using equipment listed

[11] Southeast Energy Management Corporation, Consulting Report to Adalet-PLM for Sav-A-Stop Facility Orange Park, FL.

Table 15

Control Development, Inc. Tests
Champion Pneumatic Machine Company

| Motor Description | Volts | Amps | Power | % Savings | PFC Price | Payback Period | Return on Investment |
|---|---|---|---|---|---|---|---|
| Air Compressor, 40 hp, 30<br>230/460 V, 42/21 amp | | | | | | | |
| Without PFC | 230 | 23 | 4000 | 15.0 | No further information given | | |
| With PFC | 180 | 18 | 3400 | | | | |
| **Carr Lumber & Manufacturing Co.** | | | | | | | |
| Table Saw, 5 hp, 30<br>240 V, 2.6 amp | 240 | 2.62 | 750 | | | | |
| With PFC | 142 | 1.25 | 200 | 73.3 | 392.00 | 33 | 36.7 |
| Ramco 36" Belt Sander<br>20 hp, 30, 220/240 V, | 240 | | 1400 | | | | |
| 50.8/25.4 amp<br>With PFC | 160 | 9.5 | 850 | 39.3 | 711.00 | 59 | 20.2 |
| **Hoffer Plastic, Inc.** | | | | | | | |
| Lesson 7.5 hp, 30<br>230 V, 23 amp | 230 | 6.9 | 1600 | | | | |
| With PFC | 127 | 6.6 | 840 | 47.5 | 588.00 | 15* | 78.6* |
| **Abrasive Forms Inc.<br>Carr Lumber & Manufacturing Co.** | | | | | | | |
| Surface Grinder<br>(No information given) | 232 | 12 | 1840 | | | | |
| With PFC | 180 | 9.2 | 540 | 70.7 | 392.00 | 14 | 87.0 |
| Kessler Surface Grinder<br>5 hp, 30, 220/440 V,<br>13/6.6 amp | 232 | 12 | 1040 | | | | |
| With PFC | 180 | 9.2 | 540 | 48.1 | No further information given. | | |
| **Habetler Bowling Center** | | | | | | | |
| Brunswick Pinsetter G.E.<br>1 hp, 10, 115/230 V, | 235 | 500 | | | | | |
| 12.2/5.6 amp, 1725 rpm<br>With PFC | 220 | 400 | 20.0 | | | | |
| Brunswick Pinsetter Dayton<br>1 hp, 10, 208/230 V, | 240 | 750 | | | | | |
| 1740 rpm<br>With PFC | 230 | 380 | 49.3 | | No further information given | | |
| Ball Return Dayton 6K361<br>0.5 hp, 10, 115/230 V | 240 | 300 | | | | | |
| 9.8/4.9 amp, 3450 rpm<br>With PFC | 189 | 200 | 33.3 | | | | |
| Ball Lift Century<br>0.25 hp, 10, 115 V<br>5 amp, 1150 rpm | 120 | 120 | | | | | |
| With PFC | 96 | 80 | 33.3 | | | | |

*This value included a saving of 380 watts in air conditioning.

in Table 16. These measurements were made on three 3-phase motors, a 1.5-hp conveyor, a 5-hp trash conveyor, and a 1.5-hp elevator. Data obtained for the conveyor motor showed an energy savings of 31.8 percent attributable to the PFC. Of that 31.8 percent, a 22.6 percent savings resulted from reduced motor power consumption and 9.2 percent from reduced distribution losses and air-conditioning requirements. The distribution loss reduction occurs because less current flows to the motor as a result of reduced motor power dissipation. The air-conditioning savings, which result from decreased motor heat dissipation, is for 6 months of a year with an HVAC coefficient of performance of 2.0. Annual savings of $20 for the 1.5-hp conveyor were calculated on the basis of a cost of $0.08/kWh. Data for all three motors are provided in Table 17. Note that partial data is given for the trash conveyor; this is based on the savings of the 1.5-hp conveyor and was not measured directly.

Motor power factor without the PFC was 30 percent, 42 percent, and 35 percent for the elevator, conveyor, and trash conveyor, respectively. With the PFC in line, power factor improved to 94 percent. Without the PFC, skin temperature was 115.1°F for the elevator and 120.2°F for the 1.5-hp conveyor. With the PFC, skin temperature improved to 92.9°F and 83.7°F, respectively, for elevator and conveyor.

Table 16

Equipment Used in SEMCO Analysis

Elevator Motor MLINE 1.5 hp

Conveyor Motor MLINE 1.5 hp

Trash Conveyor Motor 5 ·

Electronic Relay PM 4803-3 PFC

Energy Devices PFC 4020 PFC

IVECO EY1027 B/C PFC

Nordic ES-3 PFC

Watt Wizard PFC-221-2-460 PFC

Sangamo Induction Type Watt Hour Meter

Cramer #63SK Elapsed Time Recorder

AEMC Corp Power Factor Meter #138.100

IMC Instruments Model 2100 Digital Thermometer

Table 17

SEMCO Test Results

| | Elevator | Conveyor (1.5 hp) | Trash Conveyor (5 hp) |
|---|---|---|---|
| Operating Hours/Week | 40.9 | 60.0 | |
| Operating Hours/Year | 2127 | 3120 | |
| kWh Consumed Per Year | 732 | 733 | 1147 |
| Cost $/Year | $61 | $62 | $96 |
| Rate Factor kWh/Hr | 0.344 | 0.235 | |
| With PFC: | | | |
| Rate Factor kWh/Hr | .204 | .182 | |
| % Power Savings | 40.7% | 22.6% | |
| Distribution: | 12.5% | 9.2% | |
| HVAC % Power Savings | | | |
| Gross % Power Savings | 53.2% | 31.8% | 31.8% |
| Savings ($/yr)* | $33 | $20 | $31 |

*Based on $0.08 per kWh cost.

At the time of the analysis, SEMCO estimated PFC cost at $115 for 1.5-hp installations and $165 for 5-hp motors. Federal tax credits of 10 percent were available and used in the cost analysis. SEMCO predicted energy costs would increase 7 percent the first year after installation and 12 percent every year thereafter. Table 18 outlines SEMCO's findings.

SEMCO concluded that the installation of PFCs be recommended based on power savings from 53.2 percent to 31.8 percent. Additional benefits include improved power factor, greater motor life due to decreased operating temperature, soft start feature, easy installation, and a quick payback. SEMCO calculated a return on investment of 47 percent for the first year of operation and 186 percent over 5 years.

## Indianapolis Power and Light Company Study

A case study done by Indianapolis Power and Light Co. (IPALCO) found that a Nordic ES-1 PFC showed energy savings when connected in line with machine tools.

Table 18

Payback Periods

| Savings Application | PFC Cost | Payback 1 yr | 5 yr | (Months) |
|---|---|---|---|---|
| Elevator | $115 | $67 | $298 | 24 |
| Conveyor (1.5 hp) | $115 | $53 | $208 | 34 |
| Conveyor (5 hp) | $165 | $78 | $312 | 32 |

The test consisted of monitoring a Black & Decker bench grinder and an Atlas drill press (both single-phase units). IPALCO measured the line current, line voltage, apparent power (VA), power (watt), phase (lagging), shaft speed, and motor power factor. Measuring devices used were Westinghouse Phasemeter 435, Westinghouse Wattmeter, Data Precision 248, General Radio Strobe, and a Weston Voltmeter. The test results are given in Table 19.

IPALCO did not measure $\bar{VA}$ and power factor directly. They were calculated as follows:

$$\bar{VA} = \tilde{V} \cdot \tilde{I} \qquad \text{[Eq 11]}$$

$$Pf = \frac{P}{VA} \qquad \text{[Eq 12]}$$

where $\tilde{V}$ and $\tilde{I}$ are the mean voltage and current.

Table 19 shows that current flow drops off with the PFC in line. However, voltage supplied to the device remains constant. The power savings occur when the device is operated at no load. For the bench grinder and drill press, power savings are 56.5 percent and 32.6 percent, respectively. Apparent power savings occur under both load and no load conditions which implies that reactive power dissipation diminished, allowing for an improvement in power factor. IPALCO's calculations do not show the power factor improving greatly under no-load conditions; yet when the motor has a load, power factor improves to a greater extent.

IPALCO did not convert power savings into dollars nor did they provide data showing a probable payback period and a return on investment. Their results do indicate, however, that a single-phase PFC would be well suited to machine tools.

## Arthur D. Little Inc. Study

A paper by Martin L. Cohen of the Arthur D. Little consulting firm takes a market evaluation approach to the PFC, analyzing some interesting questions:[12]

1. What are realistic energy savings from PFCs?

[12]Martin L. Cohen, The Case for the Power Factor Sensing Motor Controller (Arthur D. Little, Inc., 1980).

Table 19

IPALCO PFC Test Results

Black & Decker 8-in. Heavy Duty Bench Grinder

115 V  9.75 amp  3/4 hp  3600 rpm

| | I | V | VA | WATT | $0_{LAG}$ | rpm | % PF |
|---|---|---|---|---|---|---|---|
| No load | 6.3 | 120 | 756 | 115 | 81.0° | 3600 | 15.2% |
| Loaded | 6.75 | 119.5 | 806.6 | 300 | 70.0° | 3570 | 37.2% |
| With ES-1 | | | | | | | |
| No Load | 3.3 | 119.5 | 394.4 | 50 | 87.0° | 3580 | 12.6% |
| Loaded | 5.61 | 119.0 | 667.59 | 300 | 65.0° | 3560 | 44.9% |

Atlas Drill Press

115/230 V  7.6/3.8 amps  1725 rpm  .5 hp  @ 120 V

| | I | V | VA | WATT | $0_{LAG}$ | rpm | % PF |
|---|---|---|---|---|---|---|---|
| No Load | 5.4 | 119.5 | 645.3 | 175.0 | 76.0° | | 27.1% |
| Loaded | 5.4 | 119.5 | 645.3 | 200.0 | 75.0° | | 31.0% |
| With ES-1 | | | | | | | |
| No Load | 3.3 | 119.8 | 395.3 | 18.0 | 76.0° | | 29.8% |
| Loaded | 4.1 | 119.8 | 491.2 | 200.0 | 70.0° | | 40.7% |

2. What price PFCs will these energy savings justify?

3. What is the PFC's major competitor?

4. In what range of motor sizes does the PFC market lie?

5. How big is the market for PFCs?

Cohen's approach to the PFC was to postulate hypothetical operating conditions and then apply cost analyses. No measurements were made nor were any PFCs operated or tested. The objective was to determine if PFC use is economical.

Cohen gives some aid in selecting the motors most appropriate for PFC use. Generally, low efficiency motors are best suited for PFCs because the potential for energy savings is greatest. Motor efficiency is a function of size and design. For instance, the more compact "T" frame motor is less efficient than the bulky "U" frame. Also, as size and rated horsepower increase, motor efficiency also increases. For example, a 75-hp motor is about 80 percent efficient and a PFC might not be justified. Figure 28 shows how motor efficiency varies with motor horsepower rating. Comparing high and low efficiency motors with similar characteristics, a 5 to 10 percent reduction in power consumption is realized with the high efficiency type,

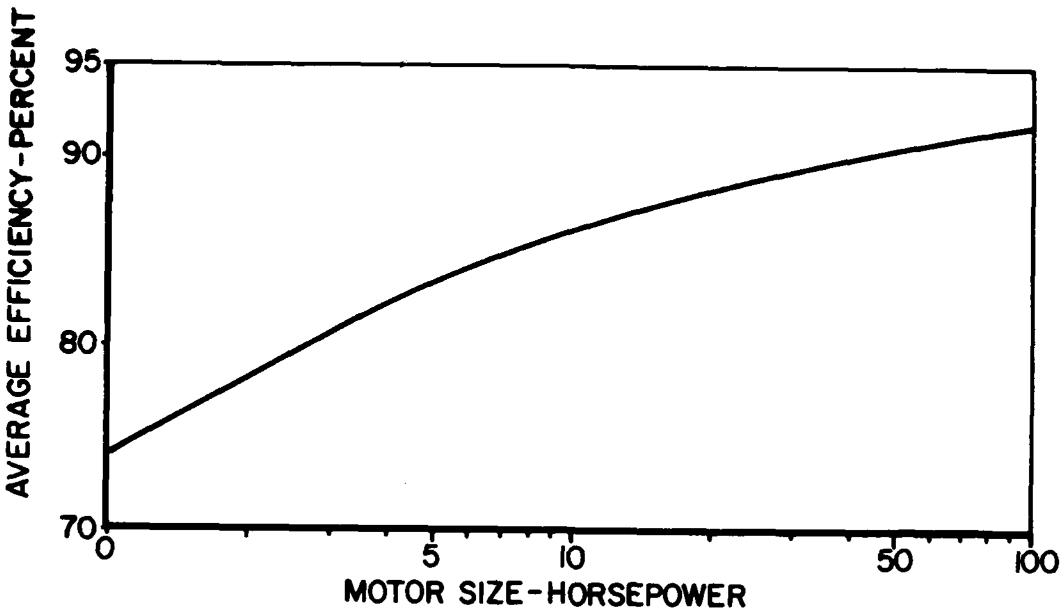


Figure 28. Average motor efficiency vs horsepower.

rated at 1 hp. This savings is relatively constant over the possible range of load, whereas a low efficiency motor controlled by a PFC has a variable savings over the same range of load.

Another criterion for selecting a motor for PFC operation is load scheduling, i.e., the time the motor operates at a given load. For example, a particular schedule may call for operation at 18 percent of full load for 60 percent of motor operation time, and the remaining operation time is at 75 percent load. Figure 29 shows how efficiency varies with load for a typical polyphase induction motor. Note that for loads below 34 percent, efficiency increases rapidly for small load increases. This load schedule must be such that the motor operation is at low loads for effective PFC operation. Two points become obvious: (1) the PFC has the greatest potential for energy savings in this area, and (2) the motor is least efficient in this area. However, predicting load schedules is difficult in most circumstances.

Other factors that affect PFC selection are electricity costs and annual hourly operation of the motor. Areas where electricity costs are high are better suited for PFC installation than those where electricity is relatively cheap. Additionally, as the hourly operation of the motor increases, greater savings occur, resulting in a shorter payback period. A poor application for the PFC would be a motor which is run only intermittently.

A straightforward economic model is presented in Equation 13 under the assumption that the motor runs at either full load or no load.

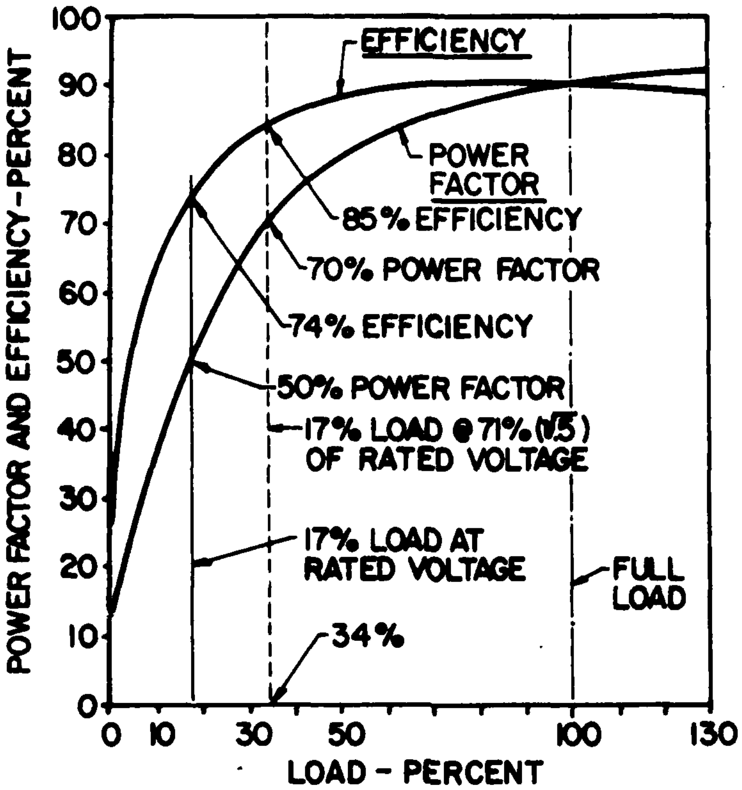


Figure 29. Efficiency and power factor of a polyphase induction motor.

$$\$S = 0.746 \times HP \times H \times F \times C \qquad \text{[Eq 13]}$$

where:

$S = Dollar savings per year attributable to PFC

HP = Rated motor horsepower

H = Hours per year running light,
where $H = H_T$ (1-loading factor)
(loading factor = fraction of time fully loaded)

$H_T$ = Total operating hours

F = Fractional loss reduction referred to full load output.
A function of efficiency, η (as shown in Figure 29)
F = 2/3 (1/ η -1) for T-frame motors
F = 1/3 (1/ η -1) for high efficiency motors

C = Cost of electricity $kWh

Knowing the dollar savings per year due to the PFC allows a realistic price for the PFC to be calculated. This price, given in dollars per horsepower, is calculated by Equation 14.

$$P = \$S \times Y/HP \qquad [Eq\ 14]$$

where Y is the number of years for the desired payback.

Cohen introduces the concept of "Figure of Merit" (FOM) in his analysis. FOM, which indicates potential energy savings for a particular size motor, is the product of percent energy (%E) used by a particular motor and the average loss for that motor (1- η ) as shown by Equation 15.

$$FOM = \%E \times (1-\eta) \qquad [Eq\ 15]$$

If the loading factor is known, it should be included in determining FOM.

Table 20 provides information on efficiency, hours of operation, and figure of merit for various horsepowers. Some examples of determining a justifiable price for a PFC are given in Table 21.

The PFC's major competitor is the energy efficient motor according to Cohen. He states, "At present a high efficiency motor, if available, is almost always a better buy than a PFC, because the energy savings is greater over most of the operating range and the cost is less." He feels that high efficiency motors are best suited for new installations and PFCs for retrofit on inefficient motors. Motors best suited for PFC interface must have lightly loaded cycles; such motors are usually in the 3- to 50-hp range. Typically, a good application of a PFC would net a 10 percent energy savings. Though PFCs are presently very costly, this can be justified by including options such as soft start and motor protection (as described in the PG&E study). From the sample calculations provided and Figure 30 (a plot of PFC cost vs horsepower) PFC prices are too high by approximately a factor of two. From Figure 30 it is apparent that "U" frame motors are cheaper than PFCs and that a "U" frame motor is desirable when installation cost is a minimum.

The study concluded the domestic market alone for the PFC would yield $10 to $100 million per year.

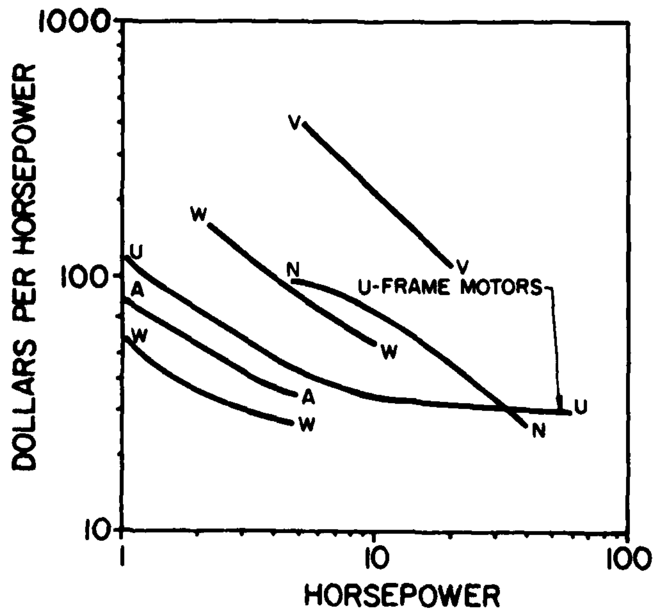


Figure 30. Cost per horsepower of U-frame motors and power factor controllers.

Table 20

Induction Motor Size Range - Horsepower

| | 1 | 1-5 | 5-20 | 20-50 | 50-125 | 125 |
|---|---|---|---|---|---|---|
| Percent of Motors: ($750 \times 10^6$ Total) | 90.3 | 7.5 | 1.4 | .5 | .2 | .2 |
| Average Efficiency, $\eta$ : | .65 | .76 | .82 | .88 | .91 | .94 |
| Average Usage: (hours/years) | 220 | 620 | 1360 | 2400 | 3300 | 3800 |
| Percent of Energy Used: ($1.4 \times 10^{12}$ kWh/yr, Total) | 2.5 | 2.8 | 8.4 | 12.6 | 27.4 | 46.3 |
| Figure of Merit for PFC Market: (% energy x $[1-\eta]$) | 0.9 | 0.7 | 1.5 | 1.5 | 2.5 | 2.8 |

Table 21

PFC Price Determination*

**Example 1:**

A 3-hp, T-frame motor operated *2000 hours/year* with a 50% load factor.
F = 0.15; H = 1000 hrs

$S = 0.746 x 3 x 1000 x 0.15 x $0.06 = $20.14/yr

P = $20.14 x 3yr/3hp = $20.00/hp for a 3-year payback.
20.14 x 2yr/3hp = $13.50/hp for a 2-year payback.

**Example 2:**

A 60% efficient 0.5 hp motor operated 2000 hour/year. With a 25% load factor. F = 0.44; H = 150 hrs

$S = 0.746 x 0.5 x 1500 x 0.44 x 0.06 = $14.77/yr

P = $14.77 x 3 yr/0.5 hp = $88.62/hp for a 3-year payback.
$14.77 x 2 yr/0.5 hp = $59.08/hp for a 2-year payback.

**Example 3:**

An 86% efficient 20-hp motor operated 4000 hours/year with a 50% load factor. F = 0.11; H = 2000 hours.

$S = 0.746 x 20 x 2000 x 0.11 x 0.06 = $196.94/yr

P = $196 x 3 yr/20 hp = $30.00/hp 3-year payback
$196 x 2 yr/20 hp = $20.00/hr 2-year payback

*Terms defined in Equation 13.

# 4 SUMMARY OF RESULTS

## Advantages

All the studies stressed the amount of power savings attributable to the PFC. The induction motors used in the PFC testing varied from 0.5 to 40 hp. All except the Northern Natural Gas report concluded that the greatest savings occurred at no or light loads, and that these savings ranged from 20 to 80 percent for the motors tested. Northern Natural Gas predicted a savings of 5 to 10 percent when a PFC is used with any motor, but, in contrast to the other studies, their graph (Figure 27) predicts the greatest savings at 70 percent full load. The differences in power savings exist because different model PFCs were tested with different motors.

It should be emphasized that although the power savings of a specific PFC vary with the different motors with which it is used, some savings will always be realized at no or light loads. As the load increases the power savings decrease, until at or near full load the power consumption actually increases. This results from losses in the PFC which are dissipated as heat. (Some PFCs have large finned exteriors to help dissipate the heat.) The maximum power consumption increase at full load was found to be 2 percent in the Pacific Gas and Electric report.

The Nordic Controls, Southeast Energy Management, and Control Development reports displayed test results for actual PFC installations. Although no estimate or measurement was made to determine percent of full load the motor operated at, the percent savings was calculated.

Most of the reports concluded that the PFC has been misnamed because it saves energy better than it controls motor power factor. Tests showed that the power factor was improved at no load but that at full load it either remained the same or decreased slightly. The Municipal Electricity Department report found a 29 percent increase in power factor at no load, while the San Diego Gas and Electric report showed a 3 percent increase at no load, but a 23 percent increase at 33 percent full load. In the testing of actual PFC installation, only Southeast Energy Management recorded power factors with and without the PFC, for three motors. The power factors for these increased 123, 168, and 200 percent, but how these power factors were determined was not mentioned.

In some of the studies the motor skin temperature was measured and found to decrease when the PFC was used. It is assumed that motor life will be extended because of the temperature reduction.

Another feature of some of the PFCs tested was "soft start," which reduces current surge. Pacific Gas and Electric tested this feature and found that the initial current surge was reduced 30 percent at full load and 19 percent at light loads.

## Disadvantages

Some of the problems encountered with PFCs have been harmonics, stability, possible motor speed reduction, and the possibility of developing a pulsating torque which could adversely affect the motor life.

Only the Pacific Gas and Electric study and the Municipal Electricity Department study examined the induced line harmonics caused by the PFC. Both studies reported that harmonic VA increased a maximum of 45 percent at partial loads, but decreased at full load by 60 percent for the 25 hp General Electric motor tested. Most of the increase in harmonic VA occurs below 450 Hz. Since the increase in harmonic VA can affect an electric power distribution system, cause electromagnetic interference, and may cause problems with nearby sensitive electronic equipment, many PFC manufacturers have added harmonic filters to the devices to prevent high oscillating harmonic VA or distortions.

Some of the PFCs tested have been unstable, but according to one manufacturer, a PFC will usually fail in the first week of operation if it is going to fail at all. (The estimated lifetime for a PFC is 20 years.)

Some studies predict a 2 to 3 percent speed reduction at full load, but this has not been proven and might vary with the type of PFC.

Development of a pulsating torque could adversely affect the longevity of the motor or increase maintenance. Not much is known about this pulsating torque effect. Its occurrence could be motor specific or PFC specific and its possible effect on motor lifetime has not yet been determined.

## Cost Analysis

In most of the PFC case studies, the annual savings were calculated by:

1. Measuring the kW savings per hour (the difference between the energy consumption without and with the PFC).

2. Multiplying the savings by the number of hours of operation per year to get the approximate annual PFC-related savings. (Because the PFC helps reduce motor skin temperature, the annual savings due to reduced air conditioning was sometimes included in this calculation.)

3. Determining the payback period by dividing the manufacturer's cost of the PFC by the annual savings. (Figure 31 shows how PFC prices vary with voltages and motor horsepower rating.) If a tax credit applied, its amount was added to the annual savings value and then the payback period was calculated.

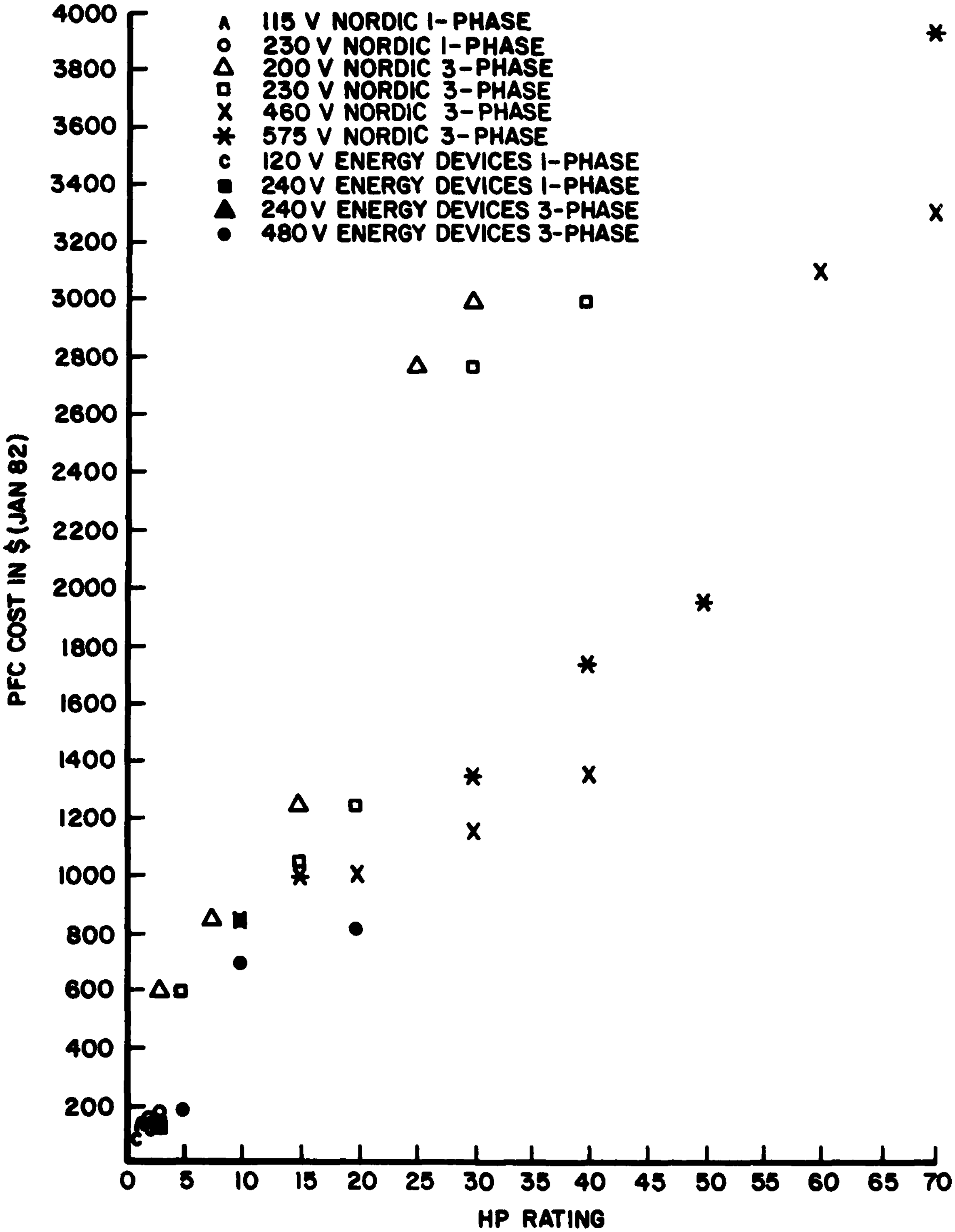


Figure 31. One- and three-phase PFC price vs horsepower.

# 5 CONCLUSIONS AND RECOMMENDATIONS

## Conclusions

An examination of studies conducted on the power factor controller has shown that it can be an effective energy conservation device when properly applied, cutting motor energy consumption by at least 10 percent on low-efficiency motors. However, the use of high efficiency motors is almost always more energy conservative, and power factor controllers do not improve the performance of motors whose efficiency is already high over the load range.

There appear to be no serious drawbacks to the installation and use of power factor controllers. Problems caused by the generation of harmonics and the occurrence of motor instability have been reported but can be resolved by working with the PFC manufacturer.

The following guidelines should be followed in selecting an appropriate PFC application:

1. It is not possible to predict precisely the energy savings which will occur without actually installing the power factor controller. While some savings will result from any installation on a low efficiency motor, the best candidate sites are those with many identical motors. One power factor controller can be purchased and used to determine the economic feasibility of a large-scale installation.

2. Motors suitable for PFC application are those that have one or more of the following characteristics:

- They are operating well below full load for most of their operating time,
- They have long operating periods,
- They are "T" frame design,
- They are running hot,
- They are rewound.

To determine the motor load conditions, use a clamp-on ammeter while the motor is operating its typical function. Record the current level and the time it remains at each level. Based on these results and the motor nameplate voltage, calculate the power for each current level found using a typical three-phase power equation. Compare these values to the expected full load power to determine the percent load conditions. Then determine the amount of time the motor is at each load. If the motor operates below 50 percent load most of its operating time, a PFC compatible with the motor should be installed.

3. When purchasing a PFC, the engineer should work closely with the PFC supplier to insure it is properly applied. Suppliers should be sought who are willing to provide lists of past customers and PFC installations.

## Recommendations

It is recommended that power factor controllers be used as a retrofit energy conservation measure when their cost is low compared to the cost of replacing existing low efficiency motors with high efficiency motors. High efficiency motors should be selected when new motor-driven equipment is purchased.

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